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Tile Drainage Systems Management and Conservation

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Abstract

The amount of U.S. crop acreage drained by subsurface tile systems increased by approximately 18 million acres from 1980 to 2022. Tile drainage can increase crop productivity in fields with poorly drained soils and can be a valuable long-term investment. However, installing tile drainage alters the hydrology of farm fields and can promote the leaching of nitrate-N and dissolved reactive phosphorus to downstream waters. Using the data from the U.S. Department of Agriculture's Census of Agriculture, Agricultural Resource Management Survey, and administrative records, this report details trends in tile drainage usage, as well as the joint adoption of tile drainage and other management practices. Tile drainage systems can involve a suite of conservation practices that are eligible for financial assistance through USDA programs. Tile drainage remains a prominent practice on corn and soybean acreage and is increasing in use on acreage dedicated to oats or cotton. There are significant differences in nutrient management practices on tiled drained and non-tiled fields. Without controlling for other factors, data for all corn acres reveal a higher rate of nutrient application, greater use of fall application, and higher usage of nitrification inhibitors on tiled-drained acres compared to non-tiled acres. Subsurface control structures, saturated buffers, and other conservation practices that manage subsurface outflows remain uncommon throughout our sample period.

Keywords: tile drainage, water quality, Agricultural Resource Management Survey (ARMS), Environmental Quality Incentives Program (EQIP)

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Tile Drainage Systems Management and Conservation

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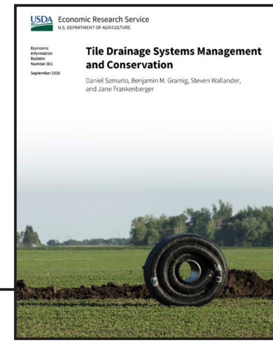


Key Points

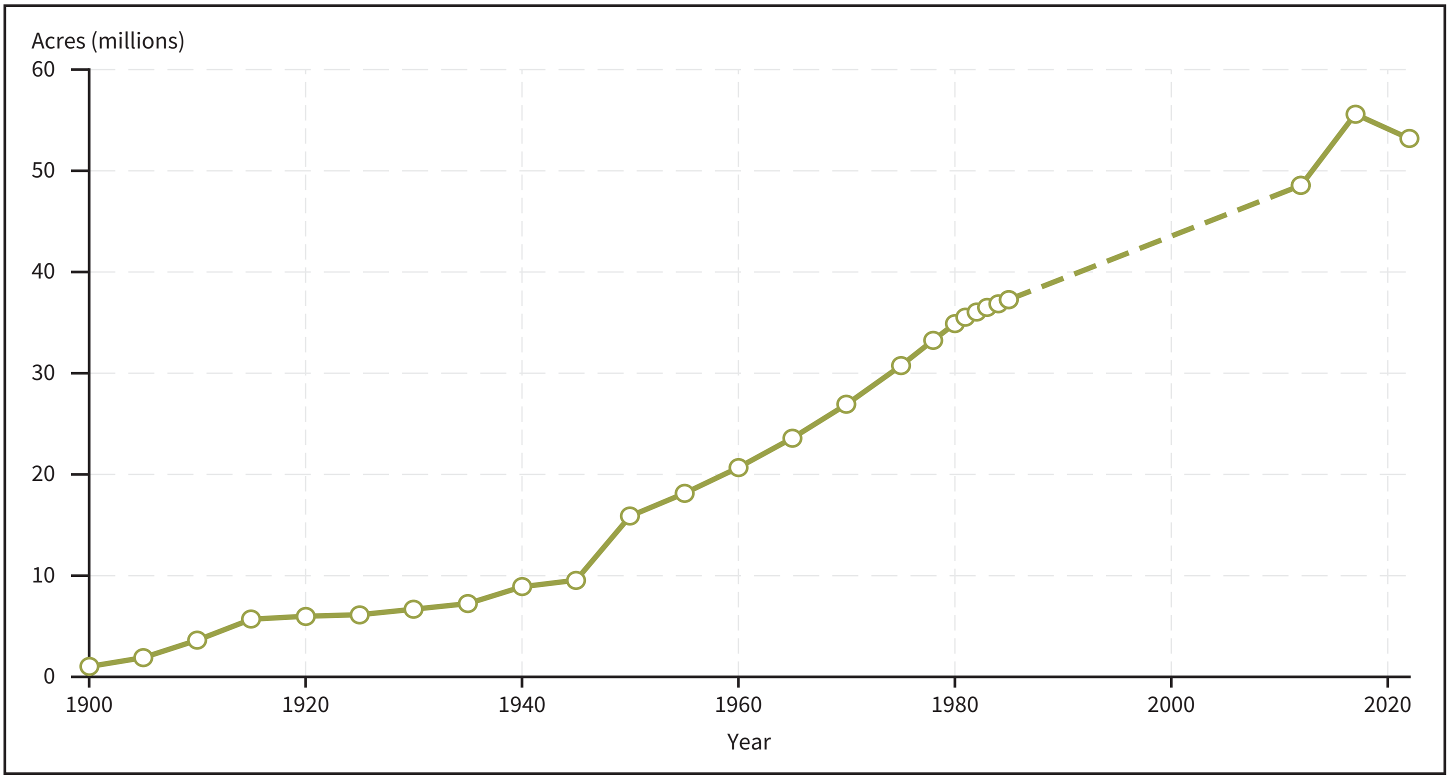
- U.S. farm acres with tile drainage have increased by 52 percent (approximately 18 million acres) between 1980 and 2022. Farm operators may also be intensifying their use of artificial drainage in certain States by installing new perforated pipes (known as tile lines) closer together, resulting in a higher density of tile lines in tile-drained fields.
- Average total applications of nitrogen fertilizer were 8 percent and phosphorus fertilizer 19 percent higher on tile-drained corn acreage in 2021 compared to non-tiled corn acreage, respectively.
- The application of nitrification inhibitors was approximately twice as common on tile-drained corn acreage in 2021 compared to non-tiled corn acreage.
- Tile-drained corn acreage was more likely to have fall application of nitrogen and phosphorous compared to non-tiled corn acreage in 2021.
- Cover crops were equally common on tile-drained corn acreage compared to non-tiled corn acreage in the Midwest in 2021.
- Thirteen percent of tile-drained corn acreage in 2021 had a control structure capable of managing subsurface outflows.
- Farmer use of financial assistance to install water-quality-improving drainage modification practices through the USDA's Environmental Quality Incentives Program (EQIP) remains low. Since 2010, fewer than 150 EQIP contracts per fiscal year have contained the Conservation Practice Standard for drainage water management. For fiscal years 2020–24, less than $1 million was allocated for saturated buffers, subsurface control structures, drainage water management, constructed wetlands, phosphorous removal systems, drainage tailwater recycling, and bioreactors combined.

Why Does This Matter?

Subsurface drainage, or tile drainage, refers to the installation of perforated pipelines beneath agricultural land for the purpose of managing soil water conditions. By increasing water infiltration through the soil, tile drainage can help ensure timely planting and harvest operations as well as minimize crop stress from excess precipitation or water stagnation in crop fields. Additionally, tile drainage enables poorly drained soil types to achieve higher potential yields, as it allows for earlier planting and pre-planting fieldwork than would otherwise be possible. This lengthens the effective growing season and allows for longer season cultivars to be planted. Although tile drainage systems offer numerous private benefits for the operator, they can increase the leaching of nitrogen and phosphorous (e.g., nitrate loads and dissolved reactive phosphorous) to downstream water bodies, contributing to water quality issues. Adjustments to drainage systems and the adoption of conservation and nutrient management practices can mitigate these water quality impacts.

Other Details

Tile-drained acreage over time



Note: No national data were collected between 1985 and 2012 (dashed line segment).

Source: USDA, Economic Research Service using data from the USDA, National Agricultural Statistics Service, 2012, 2017, and 2022 Censuses of Agriculture and Pavelis (1987).

The use of tile drainage systems, especially in the Midwest, has allowed the United States to be home to some of the most productive agricultural land in the world. Tiling supports tens of millions of acres of corn and soybean rotations providing grain for human consumption, livestock, and energy. Tile-drained acreage has steadily increased over the past 120 years, including a 4.6-million-acre increase (9.5 percent) from 2012 to 2022. Total tile-drained acreage amounts to just over 53 million acres—an area about the size of the State of Idaho. Southern Minnesota and other northern latitude regions of the Midwest—eastern South Dakota, eastern Wisconsin, Michigan, and Upstate New York—saw substantial increases in the proportion of cropland that is tile drained from 2012 to 2022.

Tile Drainage Systems Management and Conservation

Introduction

Artificial drainage systems have transformed the flat, waterlogged soils of the Midwestern United States into some of the most productive cropland in the world. Over the past 200 years, the vast majority of the prairie, comprised of wetlands and wet meadows, has been drained, unlocking the organic matter-rich topsoil for cultivation (McCorvie & Lant, 1993). Key to this monumental land conversion, and the continued productivity of the region, has been the use of subsurface (tile) drainage systems.

Tile drainage refers to the installation of pipes beneath agricultural land for the purpose of managing soil water conditions. Tile lines in poorly drained soils remove excess water by lowering the groundwater table. There are multiple private benefits from enhancing drainage—including preventing instances of crop disease, root rot, or poor nutrient uptake that can result from waterlogged soil. In addition, heavy spring precipitation can reduce field trafficability and ultimately delay pre-planting fieldwork such as tillage and fertilization, as well as planting itself. By lowering the groundwater table, tile prevents soil compaction, helps ensure timely planting, and can extend the effective growing season—allowing for higher-yield, longer-season cultivars to be planted. Tile drainage is also used to manage salinity levels on irrigated cropland in some areas.

Tile-drained acreage continues to expand—53.2 million acres of cropland were drained by tile systems in 2022, up from 48.5 million acres in 2012 (USDA, National Agricultural Statistics Service, 2014, 2024). Much like irrigation in the Western United States, tile drainage systems in the Midwestern and Eastern United States are a location-specific asset that could alter the sensitivity of crop production to changing temperature and precipitation patterns. Long-term precipitation and temperature projections differ across the continental United States (Bolster et al., 2023). While Western States are projected to experience increased severity and frequency of droughts (Hrozencik & Aillery, 2021), the Great Lakes and Midwest States are projected to experience heavier and more frequent spring precipitation (Easterling et al., 2017; Byun & Hamlet, 2018; Grady et al., 2021) and drier summers (Chen & Ford, 2022). Many older drainage systems supporting corn-soybean rotations are reported to provide insufficient drainage capacity in the face of long-term precipitation trends (Castellano et al., 2019), suggesting that the intensification of subsurface drainage systems could help ensure the viability of modern cultivars and maximize the growing season in tile-drained areas.

However, the prominent use of tile drainage on the landscape has environmental consequences beyond the initial prairie and wetland loss. The presence of tile drainage systems can alter the hydrology of a watershed (King et al., 2014; Blann et al., 2009), and in many watersheds is associated with increasing the magnitude and rate of streamflow rise and fall (streamflow “flashiness”) after precipitation events (Miller & Lyon, 2021; Zhou & Margenot, 2025) and increasing streambank erosion by widening downstream channels (Schottler et al., 2014). In addition, high amounts of nutrients (nitrate-N and dissolved reactive phosphorous[1]) are often found in subsurface drainage (Randall & Goss, 2008; King et al., 2015b). A large body of work has identified tile drains as a major source of nitrate-N in the Mississippi River drainage basin (McIsaac & Hu, 2004; Royer et al., 2006; Alexander et al., 2008; David et al., 2010). The delivery of agricultural nutrients via surface runoff and tile drainage to the Gulf of America is the primary cause of the Gulf of America Hypoxic Zone—one of the largest human-created oxygen deficient zones in the world's oceans today (Rabalais & Turner, 2019). Nitrogen delivery to coastal zones is a major contributor to harmful algal blooms, including the red tide and brown tide blooms that affect Atlantic and Gulf Coast States (Del Rossi et al., 2023). Dissolved reactive phosphorous (DRP) found in subsurface drainage is a major contributor to harmful algal blooms in freshwater bodies (King et al., 2015a; King et al., 2015b). Harmful algal blooms impact fisheries, aquatic recreation opportunities, and threaten the supply of drinking water for many U.S. municipalities (Del Rossi et al., 2023).

Adapting tile drainage systems to meet current production demands and weather patterns, while mitigating the downstream water quality impacts of tile drainage, has been a major focus of the agricultural research landscape in recent years. For example, the Conservation Drainage Network was formed in 2019 out of the existing Agricultural Drainage Management Systems Task Force as a national partnership to promote the goal of "improving drainage practices to meet future demands of crop production while reducing adverse environmental impacts of drainage" (Conservation Drainage Network, 2024). The Transforming Drainage Project (2015–21) was a USDA, National Institute of Food and Agriculture (NIFA)-funded project focused on the design and implementation of tile systems that allow for water storage in the landscape (Chighladze et al., 2021). With assistance from the scientific community, the USDA, Natural Resources Conservation Service (NRCS) established several new Conservation Practice Standards in the past 15 years that define practices that are eligible for Federal financial and technical assistance (USDA, NIFA, 2022). These practices consist of modifications to existing drainage systems to mitigate downstream water quality impacts. A subset of these practices provide drought resilience by storing drainage from springtime precipitation for use when late-season crop growth could be limited by soil water deficits.

This report outlines trends in the use of tile drainage across U.S. cropland using data from the USDA's Census of Agriculture. In addition, using nationally-representative field-level data from the USDA's Agricultural Resource Management Survey (ARMS), this report details how tile drainage is utilized—including the types of crops with which tile drainage is prevalent, which nutrient application practices accompany tile drainage, and the prevalence of jointly implemented conservation practices that can mitigate the transport of leached nutrients through tile lines. Finally, this report summarizes the past 15 years of Federal financial assistance for conservation modifications to tile drainage systems.

[1] Nitrate-N is nitrogen (N) from the chemical compound nitrate (NO_3^-) that moves with water through the soil to plant roots and to tile lines. Dissolved reactive phosphorous (DRP) is a specific form of phosphorous that moves with water through the soil profile instead of binding to soil particles and being transported to waterways, mainly through soil erosion in surface runoff. Nitrate and DRP are the primary nutrient pollutants of concern in drainage water.

How Tile Drainage Works

Tile Drainage Explained

Tile drainage systems consist of a network of regularly spaced perforated pipes or tubing buried several (3–4) feet underground that convey excess soil water to an outlet. The drains are often called tiles because they were originally made from clay tiles. Since the 1960s, they generally consist of corrugated plastic tubing installed with large drain plows or trenchers that can install thousands of feet of tubing per hour (figure 1).

Figure 1
Drain installation over time

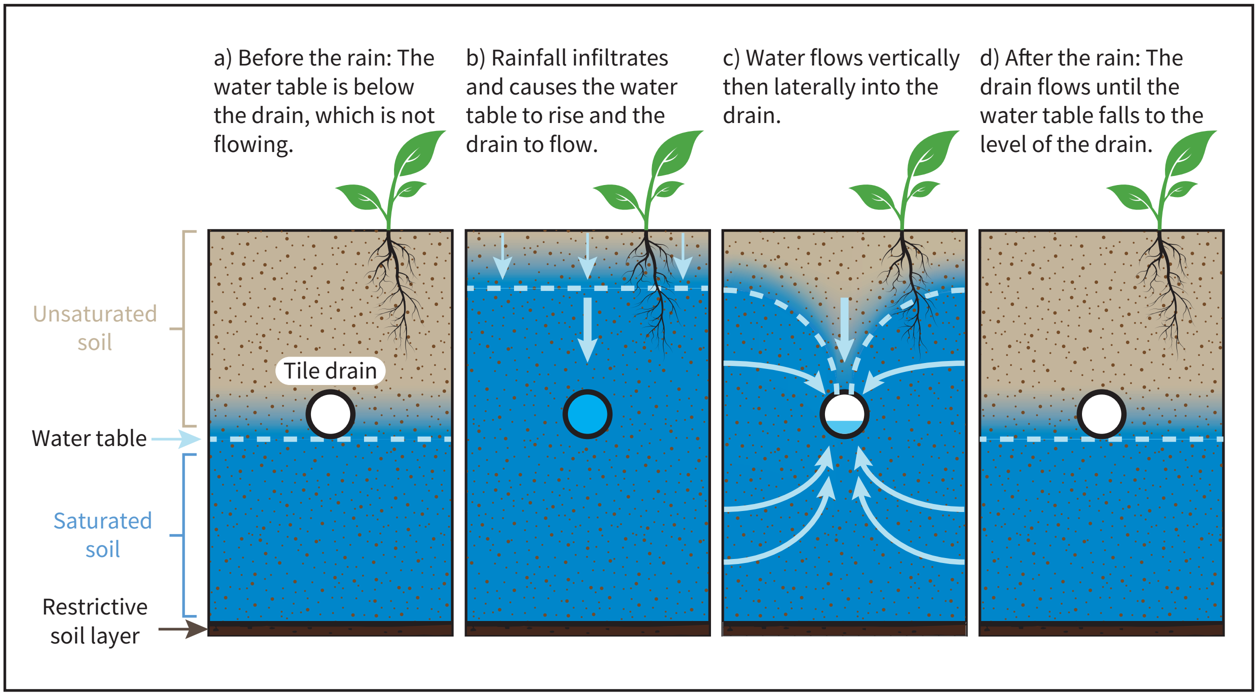
Left image: Clay tiles, widely used before about 1970, are the reason subsurface drains are often called tiles. Right image: A modern drain plow installing plastic tubing.

Source: USDA, Economic Research Service using imagery from Jane Frankenberger (Purdue University).

Crops need unsaturated soil, in which some of the pores are filled with air, to provide oxygen to the plant's roots. In naturally poorly drained soils, soil properties prevent water from leaving the field quickly enough for optimal growth. Poorly drained soils often have a restrictive layer, such as a hardpan or dense clay subsoil, that prevents water from moving downward. Artificial drainage allows excess water to be removed to provide aeration in the soil.

Tile drains are installed at a sufficient depth so the water table, which divides the saturated zone (where all soil pores are filled with water) from the unsaturated zone, is below the root zone (figure 2a). During rainfall, water that infiltrates into the soil causes the water table to rise above the drain and into the crop root zone. When saturated soil is above the drains, excess soil water flows into the drains through the perforations and is carried away from the field (figure 2b). Water in the soil directly over the drain reaches the drain most quickly, forming a gradient that causes water to flow laterally towards the drain from soil farther away (figure 2c). The drains continue to flow until the water table returns to the level of the drains. Because only water that can be drained by gravity is removed, the drains cease to flow once the water table is below the drains, leaving the soil moisture suitable for crop growth (figure 2d).

Figure 2
The drainage process



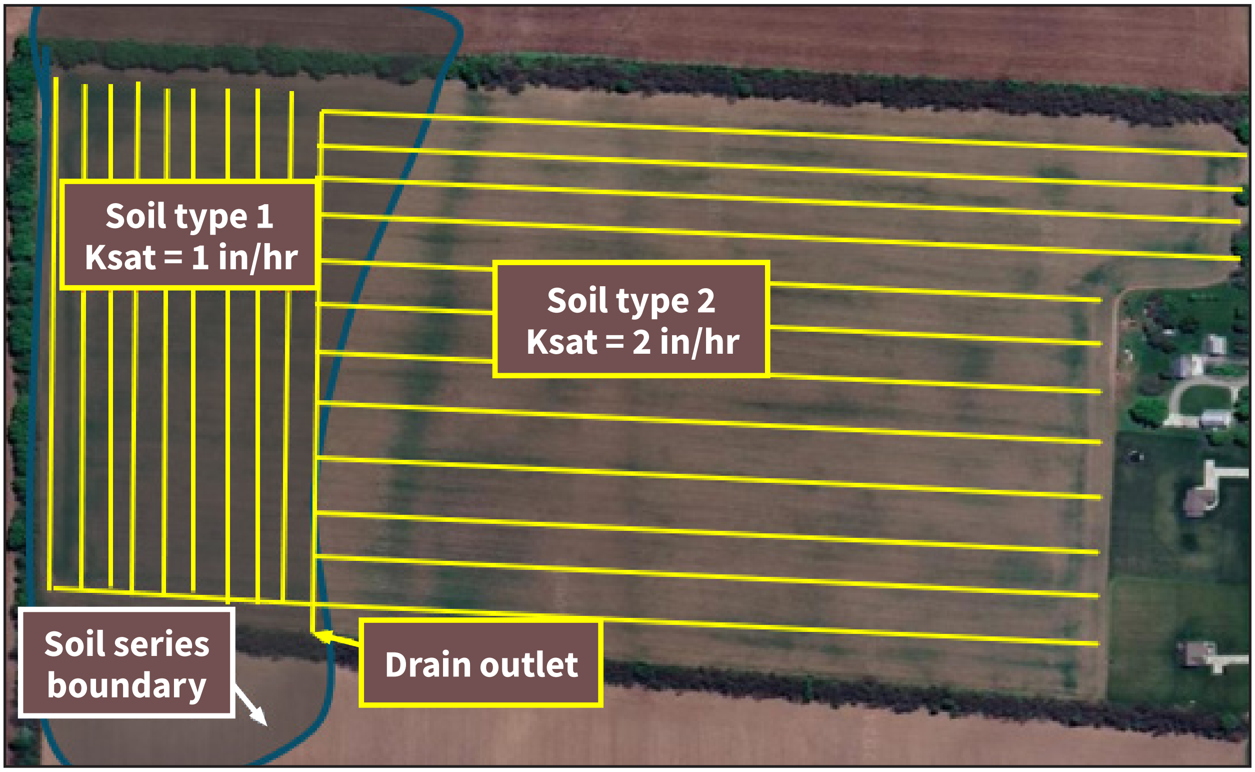
Note: Blue (darker) shading represents water saturated soil and light brown (lighter) shading denotes soil that is not saturated along a gradient from saturated (generally deeper) to unsaturated (generally nearer to the soil surface). The dashed line represents the water table that rises under more saturated soil conditions following rainfall and fills the tile line with water that flows out of field through the drain lines (b). The water table is gradually drawn down following rainfall that saturates the soil (c), eventually returning to below the tile line (d).

Source: USDA, Economic Research Service using illustrations from Jane Frankenberger (Purdue University).

The distance between drain lines, known as drain spacing or tile spacing, has a direct effect on the rate at which a field can drain. The drains are spaced at a distance that allows drainage at a rate adequate to support crop growth, usually 20–100 feet apart. Optimal spacing depends on properties of the soil, including the saturated hydraulic conductivity (Ksat) and the depth to a restricting soil.[2] Narrower spacing is needed in soils with low soil hydraulic conductivity or a shallow depth to the restricting layer, as these limit flow to the drain. Drain spacing is a primary factor in determining the cost of the system; spacing decisions must balance the potential for increased yield with the added cost of narrower spacing. Environmental concerns may also be considered, as narrow spacing increases nitrate loss through the tile drainage system. Drain spacing can vary within a field due to topographic variation and differences in soil type within the same field (figure 3).

[2] Saturated hydraulic conductivity is defined as “the ease with which a saturated soil can transmit water through the pore space” (Schoeneberger et al., 2012). This is a measure of how fast water can move through the soil profile to roots, drainage lines, and the water table.

Figure 3
Layout of an example tile drainage system



in/hour = inches per hour.

Note: Aerial view of a farm, with tile drainage tubing/pipes are indicated as yellow lines. Drain spacing in a typical tile drainage system layout is based on soil properties. It may vary within a field to address differences in the soil saturated hydraulic conductivity (Ksat).

Source: USDA, Economic Research Service using imagery from Jane Frankenberger (Purdue University).

The outlet is a critical component of a drainage system, and in some locations lack of an adequate outlet is a limiting factor for effective drainage. The outlet is often an open ditch (figure 4) or stream, pond or a wetland, or a larger pipe often managed by a regional drainage authority. The capacity of the outlet may be the limiting factor of the system's drainage rate. An elevated water level in the ditch or stream during storms due to drainage from other parts of the watershed may also impede drainage in an otherwise well-designed drainage system. If a free-flowing outlet is not available, a pumped drainage outlet may be used instead of a gravity outlet, which increases the cost of the system.

Figure 4
A drainage outlet conveys water into a ditch

Source: USDA, Economic Research Service using imagery from Jane Frankenberger (Purdue University).

The drainage rate also depends on the size of the drain tubing or pipes in the system. The smallest drains in the field are usually either 3 or 4 inches in diameter; as they converge into main drains the pipes can be much larger, 6–12 inches or more. The pipe size depends on the area drained, as well as the gradient on which the pipes are installed. The slope can be as little as 0.1 percent in flat areas, but higher slopes allow smaller pipes to convey water at a higher flow rate. The pipe size determines the hydraulic capacity of the drainage system, often referred to as the drainage coefficient, which is defined as the depth of water that can be drained in 24 hours. Many systems have historically been designed with a drainage coefficient of 3/8 inch based on standard engineering recommendations (i.e., table 5 in American Society of Agricultural and Biological Engineering (ASABE), 2015). As extreme precipitation has become more common in recent years, the drainage coefficient may be increased to lower the water table more quickly, if a sufficient outlet is available.

Yields

For the installation of tile drainage on a field to be a worthwhile investment, the costs of providing that drainage must be exceeded by the dollar-valued improvements in crop yields and crop quality which would otherwise be adversely affected by saturated soil conditions. Costs of installation vary widely based on drain size, spacing, soil types, topography, and outlet availability. Recent analyses of the economics of tile drainage installation utilize a per linear foot cost ranging from $0.81 to $1.50 (Ghane, 2022; Langemeier et al., 2023; Poole et al., 2025). USDA, NRCS estimates the cost of installation for 5-inch or smaller corrugated plastic pipe at $2.79–$2.95 per linear foot, depending on the State.[3] Assuming 40-foot spacing between lines results in approximately 1,000 feet of tubing per acre, which corresponds to an installation cost of $800–$2,950 per acre. Additional yearly costs include tile maintenance, as well as costs associated with the higher yield potential on the treated field, including added fertilizer costs. Interactive investment tools, such as Iowa State University's Farmland Tile Drainage Investment Analysis, exist to provide farmers with an estimate of the return on tile investment, tailored to their situation (Hofstrand, 2023).

[3] Estimates are from the scenario cost per unit listed under Practice 606: Subsurface Drain, Scenario #1: < = 5-inch corrugated plastic pipe in the Fiscal Year 2024 Practice Scenario Guides for Iowa, Illinois, Indiana, and Ohio (USDA, NRCS, 2023a; 2023c; 2023e; 2023f).

The impact of tile drainage installation on a field's yield levels will also vary based on soil types, topography, climate, and accompanying management practices. Table 1 displays several estimates of tile's effect on yield taken from long-term studies that examine experimental plots. Studies using experimental plots have the benefit of comparing two or more sets of fields that are generally similar in soil types, topography, climate, and management practices, with the only difference between the field sets being the drainage intervention. Yield benefits are generally more pronounced for corn than soybeans in the featured studies, although ultimately any yield effect will be impacted by site-specific factors. For example, Acharya et al. (2019a) proposes that their results, which show a yield penalty for corn on tile-drained fields, can be attributed to the lower-than-average rainfall experienced during the study period. Field-level observational data from ARMS also reveal large differences in yield expectations between tile drained and non-tiled fields (figure A.1).

Table 1
Recent studies examining the yield effects of tile drainage using experimental plots

Citation	Years	Location	Crop(s)	Findings
Wiersma et al., 2010	2001–2004	Northwest Minnesota	Wheat and soybeans	No statistical difference between yields on tiled and non-tiled fields for both soybeans and wheat.
Nelson et al., 2011	2003–2006	Missouri	Soybeans	Tiled fields produced 9–22 percent greater yields compared to naturally drained fields.
Schott et al., 2017	2011–2015	Southeast Iowa	Corn and soybeans	Non-tiled fields produced 6 percent lower corn and soybean yields compared to conventionally tiled fields.
Acharya et al., 2019a	2014–2017	North Dakota	Corn and soybeans	Tiled fields produced 5 percent lower corn yields compared to non-tiled fields; no effect on soybean yields.
Mourtzinis et al., 2021	2002–2019	Minnesota, North Dakota, Iowa, and Missouri	Soybeans	Tiled fields produced 8 percent greater yields compared to naturally drained fields.
Rui et al., 2024	1984–2020	Southeast Indiana	Corn and soybeans	Tiled fields produced 12–17 percent greater yields compared to non-tiled fields; drainage had no impact on soybean yields.

Source: USDA, Economic Research Service.

Trends in Tile Drainage

Tiled Acreage

The Swamp Land Acts of 1849 and 1850 transferred wetlands to the States for the purpose of sale to private interests. Originally drained by piecemeal efforts via ditches to limited success, it was not until the proliferation of tile drainage that mass conversion and cultivation of swamplands took place. Advancements in technology and the emergence of drainage governance institutions in the second half of the 19th century allowed for an increase in the use of tile drainage systems (Beauchamp, 1987; McCorvie & Lant, 1993; Edwards & Thurman, 2022). Throughout the decades following the Swamp Land Acts, individual States passed legislation allowing for the creation of local drainage districts. Drainage districts, with eminent domain and taxation authority, provided the coordination across landowners to route, fund, and maintain the ditches, levees, and large drainage mains that provided the outlets for individual farm tile systems.

Tile-drained acreage has steadily increased in the past 120 years, with a 7-million acre increase reported from 2012 to 2017 (figure 5).[4] This increase is consistent with high crop prices during that period which also saw low interest rates, increasing land values, and the expansion of corn acreage spurred by increases in ethanol production. High crop prices can increase the economic viability of tile drainage installation by increasing the benefit from any associated productivity bump, and this elevated income can be invested in tile and depreciated to reduce tax burden. Low interest rates reduce the total expense associated with borrowing money (e.g., to install drainage systems). Capital improvements made to the land contribute to land values and can enhance the attractiveness of investing in land that is made more productive or resilient through drainage improvements.

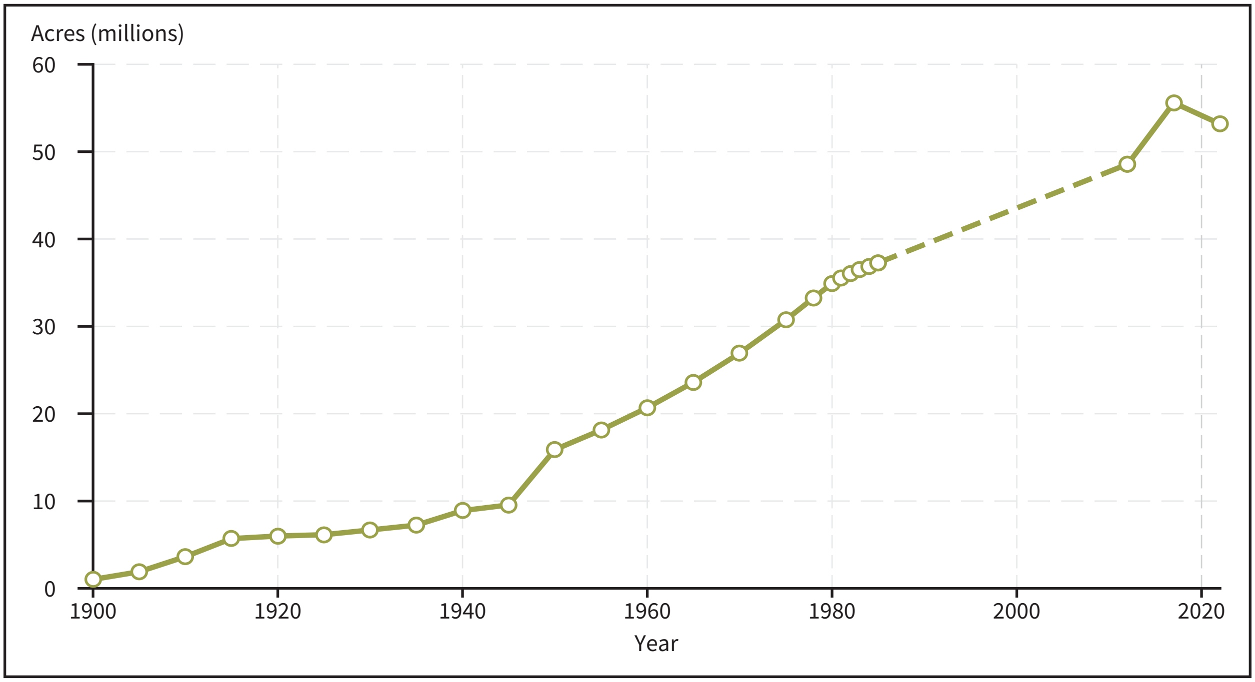
According to the Census of Agriculture, tile-drained acreage decreased by 2.4 million acres from 2017 to 2022 to a total of 53.2 million acres, rendering the net increase in tile-drained acreage from 2012 to 2022 to just over 4.6 million acres (USDA, NASS, 2014; 2019; 2024). This net increase constitutes an area approximately the combined size of Rhode Island and Connecticut. The total of 53.2 million acres is about the size of Idaho. For comparison, per the Census of Agriculture, the total amount of cropland in the United States in 2022 was approximately 382 million acres.

Iowa, Illinois, and Indiana account for 2.2 million of the 2.4-million acre decrease based on the 2017 and 2022 Censuses of Agriculture. Landowners generally do not retire tile systems or have them removed from working cropland. In addition, it is unlikely that an operator would be unaware of the presence of tile system on any of their fields (and therefore neglect to report them to the Census). Furthermore, although tile drainage systems do require some maintenance over time (e.g., protecting and clearing outlets) and there is potential for older systems to suffer permanent damage from unaddressed blockages and blowouts (Hofstrand, 2010), it is unlikely that a large share of drainage became inoperable during this 5-year period. More investigation is needed to understand the drivers of the reported reduction in tiled acres, which could be influenced by non-response to the Census.[5] These three States also reported 2.1 million fewer acres of cropland in 2022 relative to 2017. It seems likely that some of the decrease in tiled acreage can be attributed to the reduction in reported cropland acres in the 2022 Census, but determining whether these acres were converted to a different land use besides cropland will require further investigation using other land use data products beyond the scope of this report.

[4] The U.S. Department of Commerce, Bureau of the Census historically completed a Census of Drainage Organizations approximately once every 10 years from 1920 to 1978. Information about drainage was also elicited in the Census of Agriculture from 1920 to 1974. Pavelis (1987) compiled these data, along with estimates generated from the National Resources Inventory (NRI) collected by USDA, NRCS, to generate a time series of total acreage drained by subsurface systems from 1900 to 1985. Questions about drainage in the Census of Agriculture resumed with the 2012 Census (USDA, NASS, 2014).

[5] The Census of Agriculture response rate decreased from 71.8 percent in 2017 (USDA, NASS, 2019) to 61.0 percent in 2022 (USDA, NASS, 2024). Along with each yearly estimate, the Census publishes a coefficient of variation, which provides a measure of uncertainty for the estimate based on several factors, including nonresponse. The lower the coefficient of variation, the higher the reliability of estimate. The coefficient of variation for the 2022 national tile drainage estimate was 4.6 percent, up from 1.7 percent and 2.0 percent in 2017 and 2012, respectively.

Figure 5
Tile-drained cropland over time

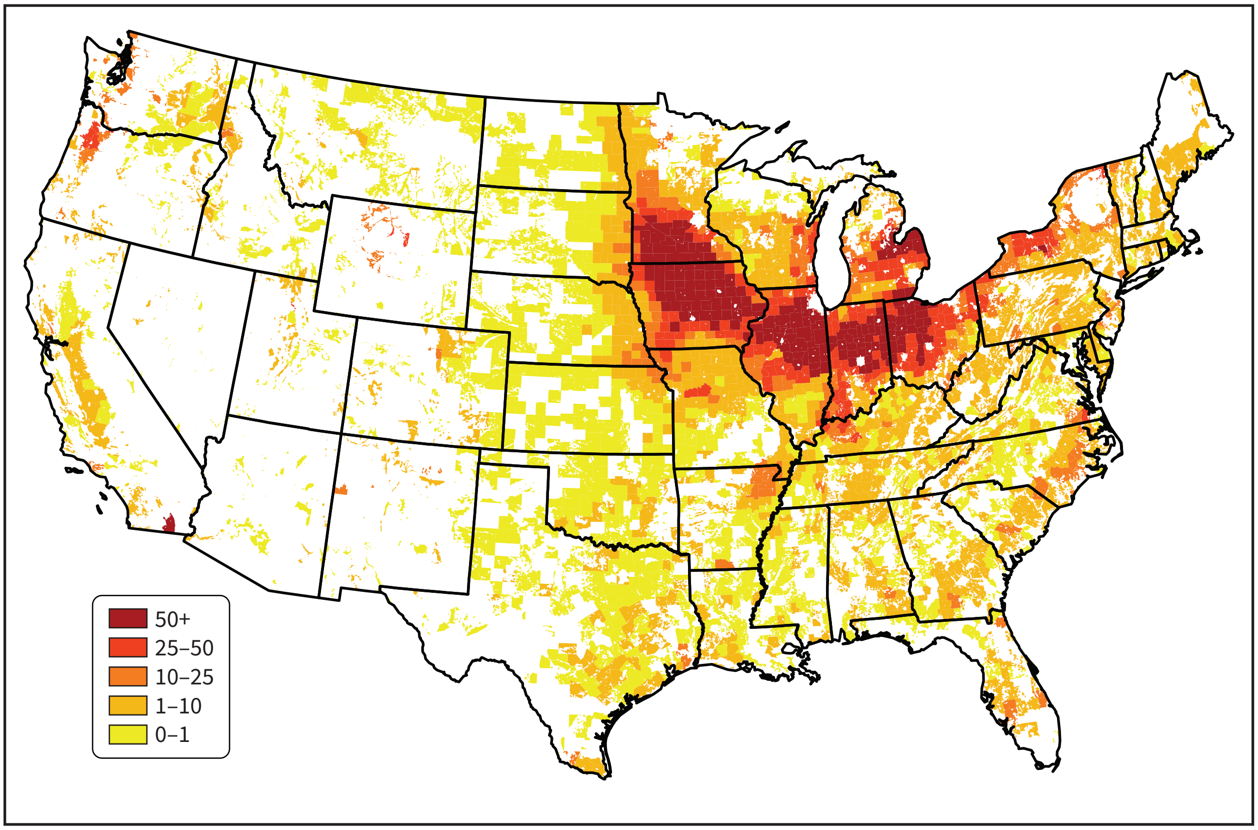


Note: No national data were collected between 1985 and 2012 (dashed line segment).

Source: USDA, Economic Research Service using USDA, National Agricultural Statistics Service, 2012, 2017, and 2022 Censuses of Agriculture and Pavelis (1987).

Tile drainage is most prominent in the Midwestern United States (figure 6). The dark red belt in figure 6 stretching from southern Minnesota to central Ohio is comprised of counties that reported more than 50 percent of cropland being tile drained in 2012. Parts of eastern Wisconsin, eastern Michigan, northwestern Missouri, northwestern Pennsylvania, and western New York are also extensively drained. Moving west to the Great Plains, tile drainage becomes much less common—the more arid climate and loamy, well-drained soils of the Great Plains make tile less necessary. Tile drainage is also prevalent in the coastal Atlantic area stretching from Florida to Virginia, soybean-growing regions in northeastern Arkansas, and the Willamette Valley in northwestern Oregon. Tile drainage is also used to manage soil salinity levels on irrigated land by leaching salts from irrigation water out of the root zone. Tile is used heavily in the Imperial Valley at the California-Mexico border for this purpose and, with less intensity, in the western half of California's San Joaquin Valley. Very small amounts of cropland use tile drainage in Alaska or Hawaii (less than 1 percent of cropland in either State). The Census does not elicit information on tile-drained acreage for American Samoa, Guam, the Northern Mariana Islands, Puerto Rico, or the U.S. Virgin Islands.

Figure 6
Percent of cropland acres that are tile drained, county level (2012)



Note: The share of cropland acres that are tiled-drained is recorded at the county level. County boundaries are clipped to show only cropland within the county. The white areas correspond to counties with no tile drainage.

Source: USDA, Economic Research Service using USDA, National Agricultural Statistics Service, 2012 Census of Agriculture.

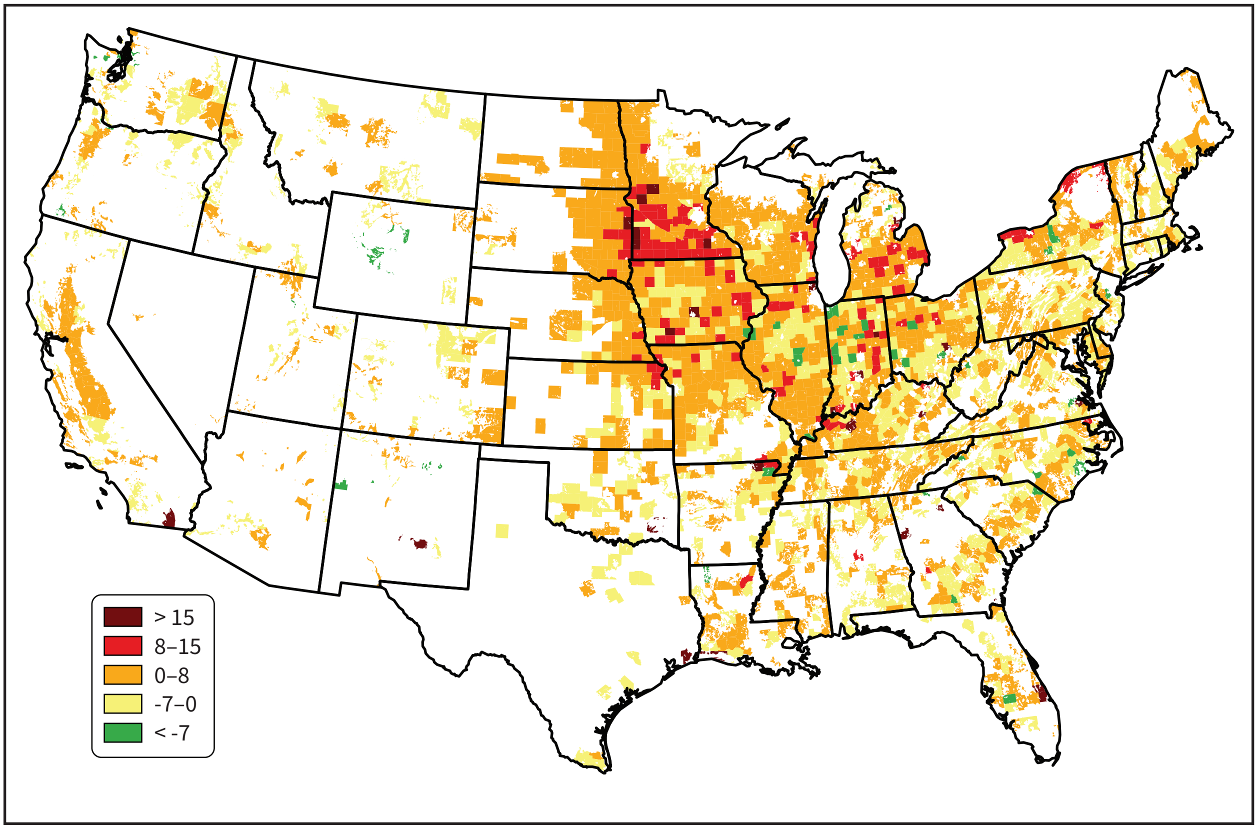
From 2012 to 2022, counties in regions positioned at relatively northern latitudes experienced substantial increases in the proportion of tile-drained cropland acreage. Minnesota saw proportion increases in both the already heavily drained south-central part of the State as well as along the western boundary with the Dakotas (figure 7). Counties at the eastern edge of South Dakota (mainly in the watershed of the Big Sioux River) experienced a similar increase, as did counties in eastern Wisconsin, eastern and central Michigan, and northern New York.

Other regions that saw the largest increases in the proportion of tile-drained cropland acreage are regions that already had significant drainage infrastructure in 2012: parts of Iowa, Illinois, and Indiana (figure 7). Numerous counties in those three States experienced decreases in the proportion of reported crop acreage that is tile drained. As mentioned previously, the decrease in total tile-drained cropland acreage observed from 2017 to 2022 was primarily driven by these three States with the highest acreages of tile-drained cropland.

Eight of the top 10 largest county-level increases in total tile-drained acreage from 2012 to 2022 occurred in Minnesota. Imperial County, California had the largest total county-level increase, with acreage increasing by 246,000 acres, or 88 percent.

Figure 7

Percentage point change in share of cropland acres that are tile drained, 2012 to 2022



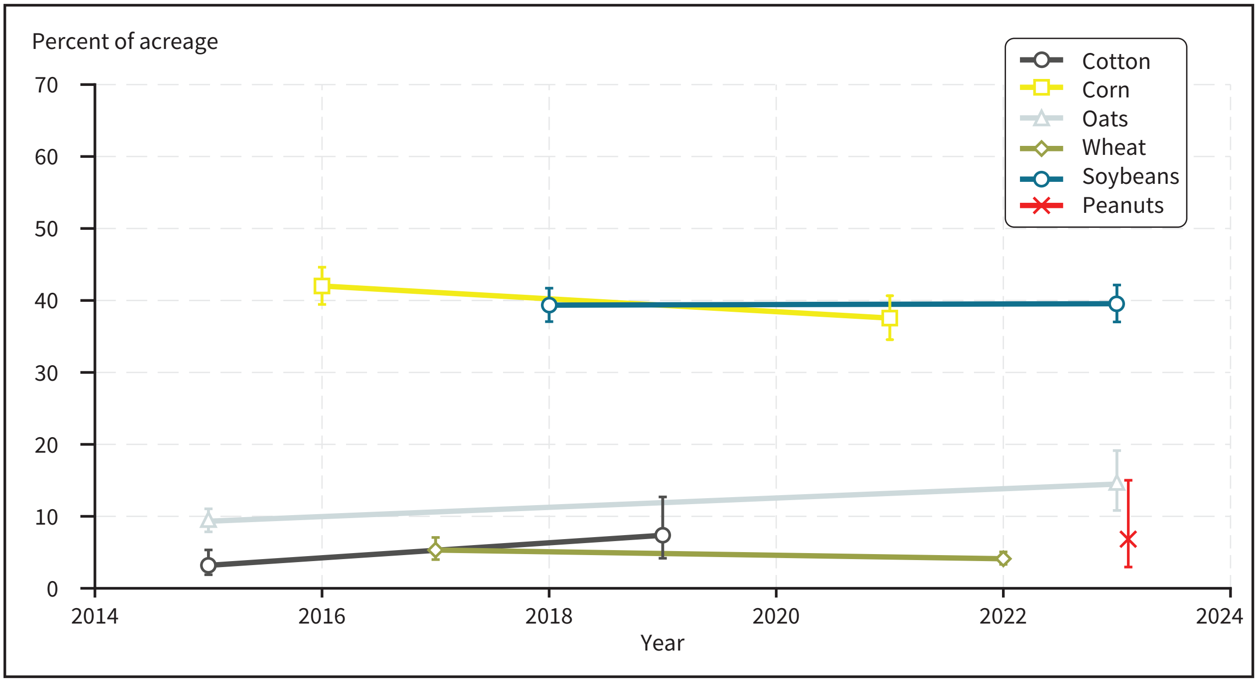
Note: Changes in the share of tile-drained cropland acres are recorded at the county level. County boundaries are clipped to show only cropland within the county. The white areas correspond to counties with no tile drainage.

Source: USDA, Economic Research Service using USDA, National Agricultural Statistics Service, 2012 and 2022 Censuses of Agriculture.

Total tiled acreage data from ARMS corroborates data from the Census of Agriculture, as well as reveals how prevalent tile is on acreage planted with specific crops. Corn and soybeans, which are primarily grown in the Midwest, have the highest proportion of total crop acreage that is tile drained (figure 8). Tile drainage is rarely reported in acreage dedicated to wheat and cotton, although tiled cotton acreage increased from 3.2 percent to 7.4 percent of national cotton acreage from 2015 to 2019 ($p < 0.05$).[6] The proportion of oats acreage that is tile drained also increased in our sample years, from 9.3 percent in 2015 to 17 percent in 2023 ($p < 0.01$), with much of U.S. oat production occurring in upper Midwestern States (Wisconsin, Minnesota, and Michigan) where tile drainage is already common. ARMS data revealed a decrease from 2016 to 2021 in the percent of corn acreage that is tiled—from 42 percent to 37.5 percent ($p < 0.05$). This reduction in tile-drained corn acreage from 2016 to 2021 in ARMS is consistent with the overall decrease from 2017 to 2022 in the Census of Agriculture. However, soybean acreage saw no change in tile-drained proportion from 2018 to 2023.

[6] P-values are the result of a statistical test. They tell us the probability that we would observe our data under a null hypothesis. The null hypothesis in this case is that two parameters, the proportion of acreage that is tile drained in the earlier year and the proportion in the later year, are equal. The alternative hypothesis is that the two parameters are not equal. A smaller p-value indicates there is stronger evidence in favor of the alternative hypothesis.

Figure 8
Percent of crop acreage that is tile drained, by crop and survey year



Note: Responses are weighted by USDA ARMS Phase II acreage weights. The vertical lines indicate 95 percent confidence intervals. Acreage percentages are estimated as proportions, hence confidence intervals are calculated using a logit transform so the bounds lie between zero and one.

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service; 2015 (Cotton and Oats), 2016 (Corn), 017 (Wheat), 2018 (Soybeans), 2019 (Cotton), 2021 (Corn), 2022 (Wheat), and 2023 (Oats, Peanuts, and Soybeans) Agricultural Resource Management Surveys (ARMS).

Tile Spacing and Drainage Intensification

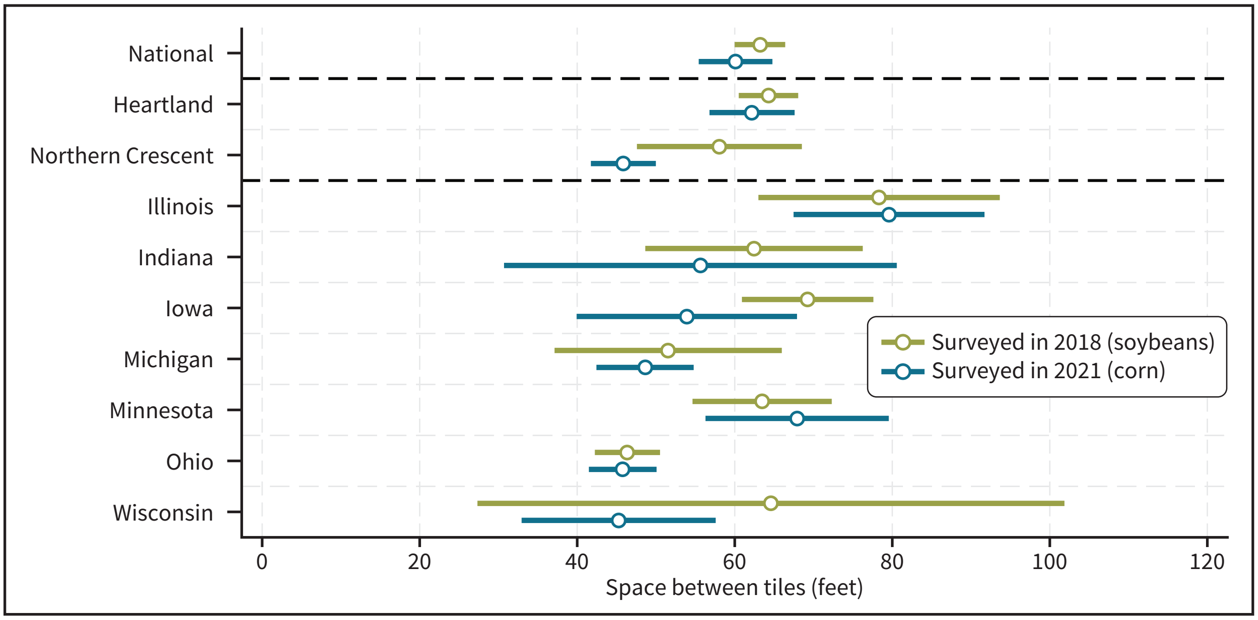
Both historical trends and long-term projections show evidence of increased precipitation in the Midwest going forward (Easterling et al., 2017; Byun & Hamlet, 2018; Grady et al., 2021). Heavy springtime precipitation threatens the ability of operators to conduct field operations and plant field crops in a timely manner. Many drainage districts and farm operators with older infrastructure likely do not have the drainage capacity to manage these long-term changes. Kanwar et al. (1983) found that 95 percent of the farmland within the upper basin of the Des Moines River was within drainage districts with district-level infrastructure incapable of managing the drainage intensity of yield-maximizing on-farm drainage systems. As mentioned previously, the capacity of the outlet ditch or pipe is a limiting factor for effective on-field drainage. Large drainage mains, surface ditches, and levees are vital to transporting subsurface drainage from fields to streams and rivers, with their construction and maintenance often under the purview of drainage districts, watershed districts, or counties, depending on the State (Schmidt, 2020). Assistance for watershed-level projects, including the construction or rehabilitation of artificial and natural drainage channels, is available through USDA, NRCS's Watershed Programs (USDA, NRCS, 2014).

Furthermore, much of the original drainage infrastructure in the Midwest was built when larger amounts of acreage were dedicated to forage crops, which require less intense drainage than the row crops that dominate the landscape today (Castellano et al., 2019). In the face of projected changes in precipitation patterns, expansion of tile drainage systems to new acreage and the intensification of existing systems have been cited as potential adaptation strategies (Bowling et al., 2020).

At the field level, tile lines that are spaced closer together drain more water from the field compared to lines spaced farther apart (Kladivko & Bowling, 2021) and through field trials are associated with higher average corn yields—especially in wet years (Acharya et al., 2019b; Rui et al., 2024). Despite this, an operator must balance the higher cost associated with installing and maintaining more narrowly spaced drain lines and the potential yield benefit of a drainage system with higher intensity. Observing 38 years of data on experimental plots in southeastern Indiana, Langemeier et al. (2023) found that across a range of installation costs, discount rates, and system lifespans, a wider spacing of 66 feet offered the highest net returns on average compared to spacings of 16 feet, 33 feet, and 133 feet (which they classify as effectively undrained), even though yields and revenues were higher on the fields with narrower spacings. Narrower drain spacing is also associated with greater nitrate-N losses (Kladivko & Bowling, 2021).

Figure 9

Average spacing between tile lines, surveyed soybean (2018) and corn (2021) fields



Note: Responses are weighted by USDA ARMS Phase II acreage weights. The horizontal lines indicate 95 percent confidence intervals.

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2018 (Soybeans) and 2021 (Corn) Agricultural Resource Management Surveys (ARMS).

Empirical evidence from ARMS suggests there has been substantial replacement and updating of field-level drainage systems in the past decade. The 2018 ARMS of soybean fields and the 2021 ARMS of corn fields asked about average spacing between in-field tile lines (the previous corn survey in 2016 and the 2023 soybeans survey do not ask this question). To the extent that surveyed soybean acreage and surveyed corn acreage are representative of the same kind of cropland in different years,[7] average spacing at the national level decreased by just about 3 feet from 2018 to 2021, although the difference is not statistically significant (figure 9). Estimates are also displayed for individual States and for the two USDA, Economic Research Service (ERS) Farm Resource Regions with the most tile drainage—the Heartland and the Northern Crescent (see figure A.2 for a map of Farm Resource Regions). The Northern Crescent region, which encompasses the northern latitudes of the Midwest and the Northeast, experienced a decrease in average spacing between tile lines from 58 feet to 46 feet ($p < 0.05$).

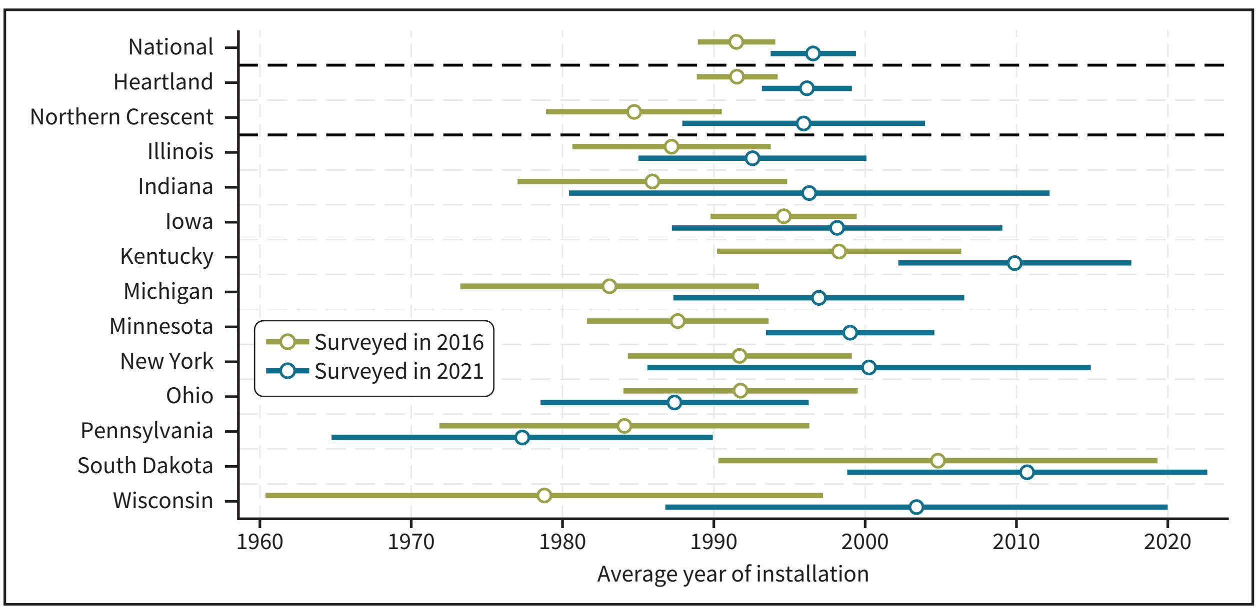
[7] The crop history information collected in the ARMS Phase II survey indicates that surveyed corn and soybean fields are representative of the same cropland in different years because these crops are most often grown in rotation with one another. This means the separate crop surveys can reliably be compared to evaluate changes in the average spacing of tiles without having to rely on the same ARMS Phase II commodity survey from a prior year.

Of the individual States, Ohio appears to have the tightest average spacing when considering both the 2018 soybeans and 2021 corn surveys. Many prominent soil types in Ohio are clay heavy (Miller & Lyon, 2021), which demand a higher drainage intensity and hence more narrowly spaced tile lines to optimize row crop production.

Much of the tile laid in the Midwest was installed in the early to middle 20th century, and many operators still utilize the original clay tiles from when the land was initially drained. Furthermore, older systems often consisted of single tile lines at different spacings and angles to address specific depressions or potholes on a field—in contrast to newer systems that are more likely to be installed in a pattern of parallel lines at equal spacing (Singh et al., 2009), commonly referred to as pattern tiling a field (similar to the depiction in figure 3). Wisconsin appears to have the most dramatic decrease in average spacing—the State is known to have had less pattern tiling historically until recent years (Ruark et al., 2017).

ARMS provides further, albeit indirect, evidence of widespread field-level drainage system replacement or updating. Between 2016 and 2021, the average year of installation of a surveyed corn field's drainage system went from 1991 to 1996 in the Heartland ($p < 0.10$) and 1984 to 1995 in the Northern Crescent ($p < 0.05$) (figure 10). Plausible reasons for this observed change in average age of installed tile include: (1) the installation of new systems between survey years on fields that did not have drainage before; (2) the retirement of corn fields that had older drainage systems or switching to different crops resulted in their removal from the survey sample; or (3) the replacement or updating of older tile systems on fields that had drainage continuously throughout the time period. Average age for tile systems on surveyed soybean fields (2018 to 2023) is displayed in figure A.3.

Figure 10
Average year of tile drainage installation, surveyed corn fields (2016 and 2021)



Note: Responses are weighted by USDA ARMS Phase II acreage weights. The horizontal lines indicate 95 percent confidence intervals.

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2018 (Soybeans) and 2021 (Corn) Agricultural Resource Management Surveys (ARMS).

Tile Drainage and Conservation Practices

Tile drainage is one component of an operation's production system. The additional management practices that comprise the full production system often vary by climate, soil type, cropping system, farm characteristics (size, rented versus owned), and operator characteristics. With tile drainage primarily located on the poorly-drained, organic matter-rich soils of the Midwest, one could expect that the production systems utilizing tile drainage may exhibit different nutrient management and conservation behaviors than systems that do not, both within and across regions. Conservation planning for these production systems can benefit from statistics on patterns in joint adoption, which are best provided by data sources such as ARMS. We produce these statistics using 2021 ARMS data on corn acreage.

Nutrient Management

Field nutrients and pesticides are critical inputs for crop production. According to the 2021 Agricultural Chemical Use Survey, 95 percent of planted corn acreage in 2021 received nitrogen fertilizer, 75 percent received phosphate fertilizer, and 96 percent received herbicides (USDA, NASS, 2022).[8] Applied field nutrients and pesticides also represent a major source of non-point source pollution in rivers, streams, lakes, and wetlands. Tile drainage can exacerbate or decrease the risk of nutrient and pesticide transport to surface waters by altering how precipitation moves off the field. By increasing soil water infiltration, tile generally reduces surface runoff in favor of subsurface flow, although results vary across different topographies, soils, and climates. Therefore, in fields with poorly drained soils and high water tables, the installation of tile drainage can reduce the surface transport of sediment and associated agrochemicals that attach (adsorb) to soil particles, including pesticides (Skaggs et al., 1994; Kladivko et al., 2001; Blann et al., 2009; Maalim & Melesse, 2013). Consequently, tile can increase the transport of agrichemicals that can leach through the soil profile, a phenomenon that may increase with the expansion of tile-drained acreage in northern Midwestern regions seen in the Census of Agriculture.

Nitrogen fertilizer that is not taken up by the harvested crop or lost to denitrification (the conver-sion of nitrate to nitrogen gas) is prone to leaching.[9] Nitrogen leaching occurs when easily dissolvable nitrogen, usually in the form of nitrate, is carried by water down through the soil profile. Tile lines then intercept the nitrate-laden water and discharge it directly to the outlet ditch or waterbody (Dinnes et al., 2002). Narrower drain spacing is associated with greater nitrate-N losses (Kladivko & Bowling, 2021). In addition, by increasing soil infiltration subsurface drainage can decrease the amount of soil sediment loss from surface runoff, including phosphorous that is attached to soil particles (Algoazany et al., 2007). However, a portion of the phosphorus fertilizer that is applied to a field can dissolve when a field receives precipitation. Rainwater can carry the dissolved reactive phosphorus down through the soil profile where it is intercepted by tile lines and carried directly to the outlet ditch or waterbody—representing an important source of phosphorus to surface water (Gentry et al., 2007). Phosphorous can also enter subsurface drainage via preferential flow, a term for runoff that directly enters subsurface drains through macropores (e.g., cracks, holes from worms and burrowing animals, holes from roots) in the soil (Blann et al., 2009; King et al., 2015a). Preferential flow is the main vehicle for pesticide transport through tile drainage, although it is generally accepted that the presence of a tile drainage system decreases pesticide loss via surface runoff more than it increases losses through preferential flow (Kladivko et al., 2001).

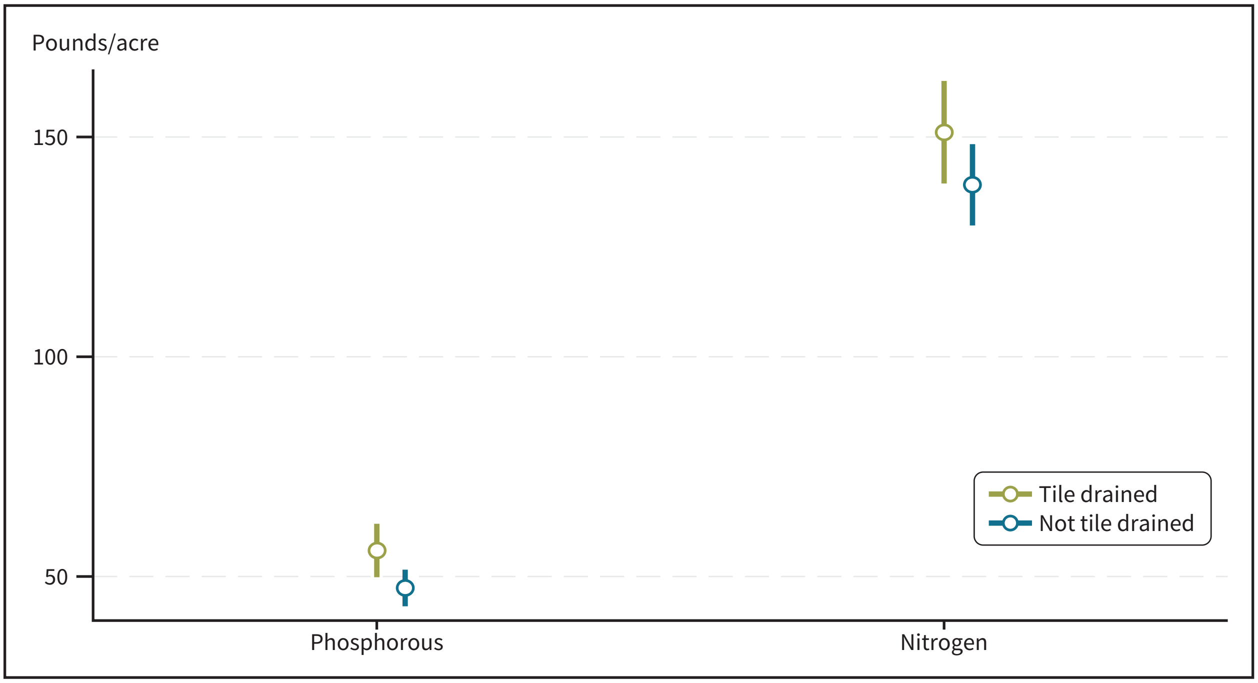
[8] The 2020 Agricultural Use Survey, which focused on soybeans, revealed that 32 percent of planted soybean acreage in 2020 received nitrogen fertilizer, 42 percent received phosphate fertilizer, and 98 percent received herbicides (USDA, NASS, 2021).

[9] Other pathways for nitrogen loss include soil erosion, surface runoff of dissolved nitrogen, ammonia volatilization, and nitrification (Ribaudo et al., 2011).

The 2021 ARMS corn data indicate that in total across the fall, spring, planting, and post-planting periods, operators apply nitrogen at a marginally higher rate ($p < 0.10$) on tile-drained corn acreage compared to non-tiled corn acreage (151 pounds per acre versus 140 pounds per acre), as well as apply phosphorous at a higher rate ($p < 0.05$) on tile-drained acreage than non-tiled acreage (56 pounds per acre versus 47 pounds per acre, figure 11). Higher application rates don't automatically imply higher nutrient losses, however. Since tile-drained fields often have greater expected crop yields, operators will apply more nutrients to account for the greater crop nutrient demand (Ribaudo et al., 2011).

Figure 11

Average total application rate of phosphorous and nitrogen by drainage status, surveyed corn fields (2021)



Note: Responses are weighted by USDA ARMS Phase II acreage weights. The horizontal lines indicate 95 percent confidence intervals.

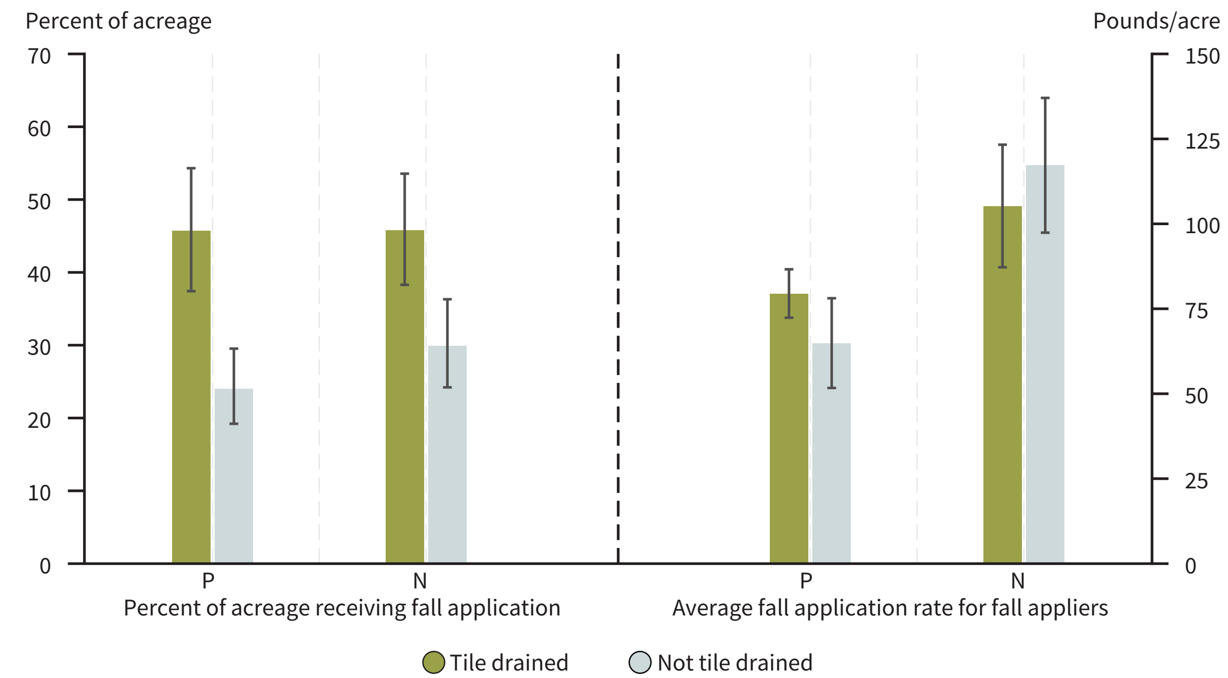
Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2016 (Corn) and 2021 (Corn) Agricultural Resource Management Surveys (ARMS).

A common framework for implementing best management practices is the "4R" framework, which characterizes good nutrient management as using the right fertilizer source, at the right rate, at the right time, and in the right place (Ward et al., 2018). The right time refers to aligning the application of nutrients with crop needs. The closer application is to the time nutrients are needed by a growing crop, the lower the chances of leaching before crop uptake. Leaching of fertilizer/manure and soil nutrients can be especially common in the fallow period when there are no crops present to take up water during a precipitation event (hence more subsurface discharge) or when soils are chronically saturated (Meisinger & Delgado, 2002; Van Es et al., 2006). The fall months of the fallow period also correspond to when operators may choose to apply fertilizer or manure for the next commodity crop planting in the spring, and any leaching event in the fallow period could consist of these recently applied nutrients. Operators choose to apply fertilizer during the fall months to minimize the risk of not having enough days suitable for field work (DSFW) in the spring before planting the next crop that will be grown in the field. When the soil is too wet, operators are unable to perform field work (e.g., tillage, fertilizer application, planting) and delayed planting may ultimately affect yields at harvest.

Applying fertilizer in the fall, when the soil is most likely drier, saves time in the spring and frees up valuable DSFW for other operations (Gramig et al., 2017). Nitrogen fertilizer is also usually less expensive in the fall compared to the spring and summer months (Schnitkey, 2016).

Historically, most operators apply fertilizer in a single pass in either fall or spring before planting (Gramig et al., 2017). Operators may also choose to apply fertilizer at or after planting instead. The left panel of figure 12 shows that 46 percent of tile-drained corn acreage sees fall application of nitrogen and 46 percent of tile-drained corn acreage sees fall application of phosphorous, compared to, respectively, 30 percent and 24 percent of non-tiled corn acreage ($p < 0.01$ for both nutrient comparisons). Tile-drained corn acreage appears to be managed more intensively on average than non-tiled acreage, given the higher average application rates per acre (figure 11) and the higher likelihood of fall application. Alternatively, operators on fields with poor drainage that require tile may be inclined to apply in the fall to preserve DSFW in the spring. The right panel of figure 12 demonstrates that, conditional on fall application occurring, tiled corn acreage has higher ($p < 0.05$) rates of fall phosphorous application and statistically identical rates of fall nitrogen application compared to non-tiled corn acreage.

Figure 12
Fall application of phosphorous and nitrogen by drainage status, surveyed corn fields (2021)

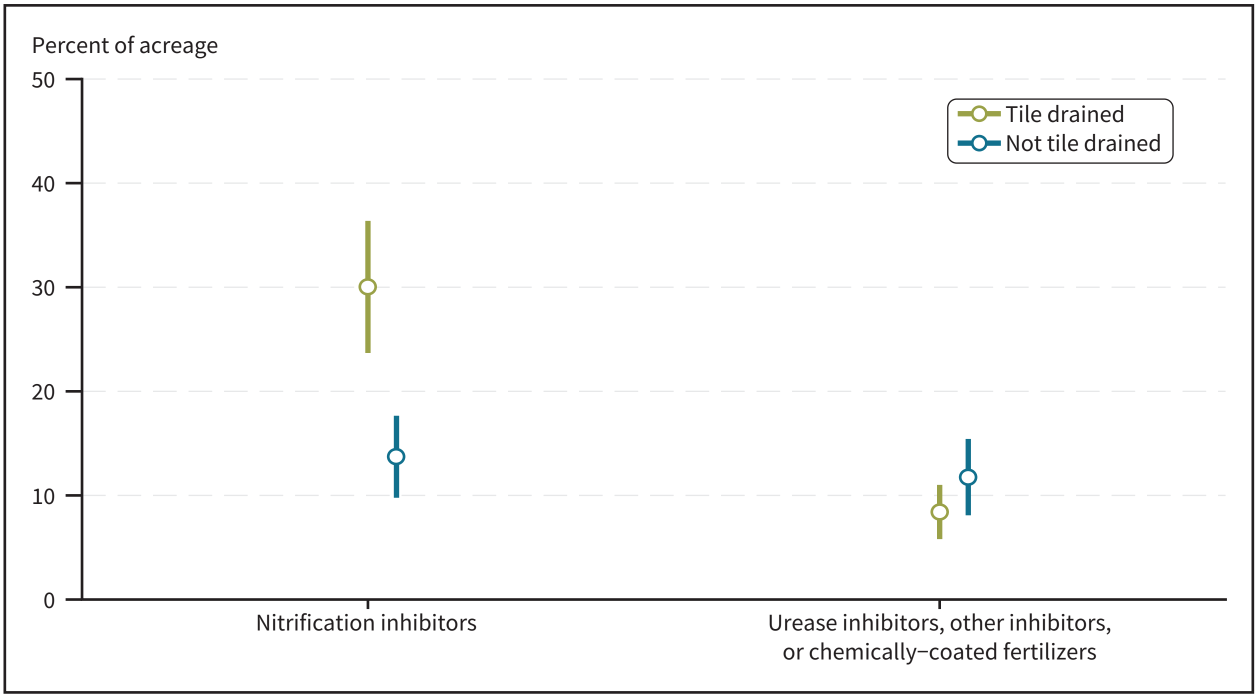


Note: Responses are weighted by USDA ARMS Phase II acreage weights. The vertical lines indicate 95 percent confidence intervals.

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2021 (Corn) Agricultural Resource Management Survey (ARMS).

Nitrogen is a valuable input that can be managed to maximize crop uptake which in turn minimizes or inhibits loss to the environment. Special fertilizer products developed to reduce nitrogen loss from farm fields are commonly referred to as nitrogen loss inhibitors. Nitrification inhibitors slow the transformation of ammonium-N to nitrate-N, reducing the loss of nitrogen fertilizer to the environment through leaching or denitrification, thus increasing nitrogen use efficiency. Urease inhibitors prevent ammonia volatilization and the loss of nitrogen fertilizer to the atmosphere as ammonia gas. In addition, chemically-coated fertilizer can delay the time at which the nutrient is able to be absorbed by plants after nutrient application. Sulfur-coated urea products act as slow-released fertilizer, in which the release of the nutrient is dependent on soil and climate conditions. Polymer-coated urea products act as a controlled-released fertilizer that is designed to release nutrients corresponding to the nutrient requirements of the crop at certain stages. While the use of urease inhibitors, chemically-coated fertilizer, and other inhibitors occured on the same proportion of tile-drained acreage compared to non-tiled acreage, 30 percent of tile-drained acreage reported using nitrification inhibitors, compared to 14 percent of non-tiled acreage ($p < 0.01$) (figure 13). As previously shown, this could align with the higher occurrence of fall nitrogen application by operators on tile-drained fields to prevent overwinter losses. Research shows that with nitrification inhibitors (and cold soils at application), fall application does not result in higher nitrate losses compared to spring application (Waring et al., 2022).

Figure 13
Percent of acreage that receives application of nitrogen loss inhibitors by drainage status, surveyed corn fields (2021)



Note: Responses are weighted by USDA ARMS Phase II acreage weights. The vertical lines indicate 95 percent confidence intervals. Acreage percentages are estimated as proportions, hence confidence intervals are calculated using a logit transform so that the bounds lie between zero and one.

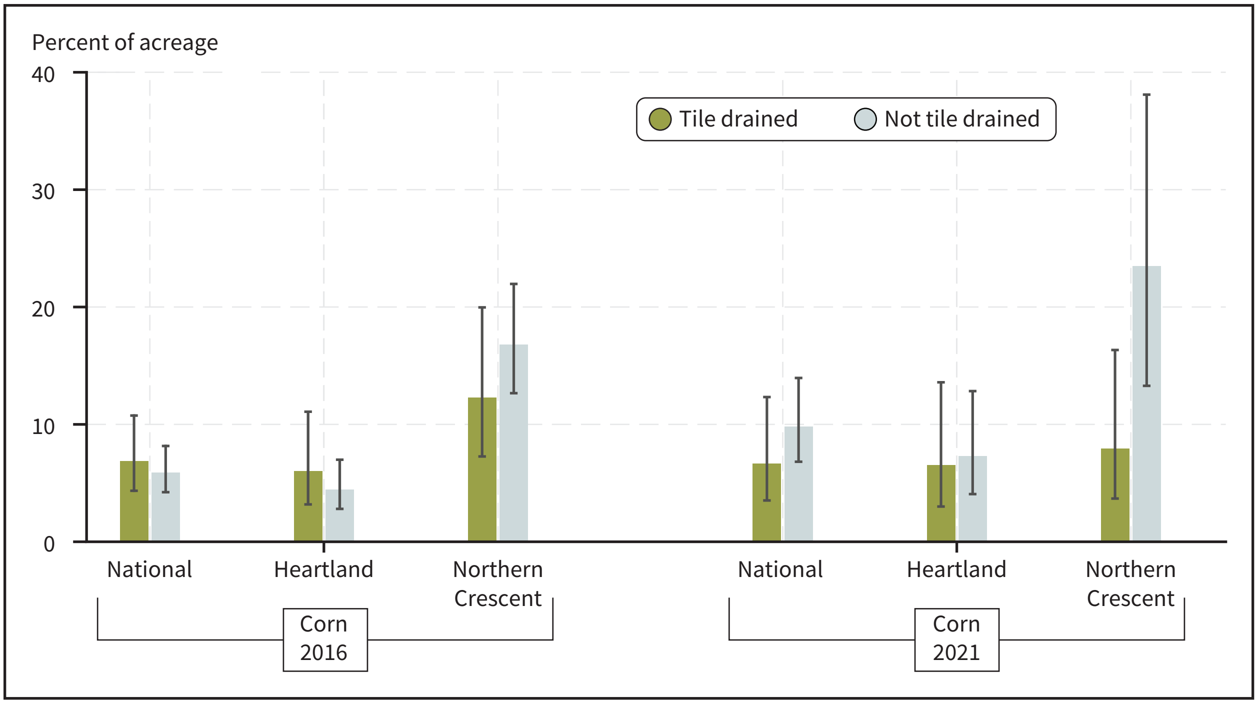
Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2021 (Corn) Agricultural Resource Management Survey (ARMS).

Cover Crops and Tillage

Cover crops are typically unharvested plantings of grasses, small grains, or legumes used to cover the soil between harvest of the prior crop and planting of the next crop. Cover crops take up excess available nitrogen and hold it in organic form as crop biomass until it is released back into the soil when the cover crop decomposes (Dinnes et al., 2002). A large body of work has demonstrated cover crops to be effective in reducing nitrate leaching (Thapa et al., 2018; Nouri et al., 2022), including on tile-drained fields (Dinnes et al., 2002; Kaspar et al., 2007). Cover crops can also sequester soil carbon (Poeplau & Don, 2015) and can be grazed or harvested for forage (Bowman et al., 2024).

Despite cover cropping's ability to reduce nutrient transport on tiled fields, total rates of cover cropping adoption are low in the tiled-drained Corn Belt States, and generally lower than rates exhibited in Eastern and Northeastern States (Wallander et al., 2021; Bowman et al., 2025). Nationally, cover cropping on tile-drained corn acreage remained largely unchanged from 2016 to 2021 in terms of proportion of cropland acreage (figure 14). Cover crop use on tile-drained acreage was statistically equivalent to non-tiled acreage in the Heartland Resource Region (the Corn Belt), but adoption was significantly lower compared to non-tiled acreage in the Northern Crescent Resource Region in 2021 (the northern Midwest, the Northeast) ($p < 0.05$), which had higher adoption than the national average.

Figure 14
Percent of acreage that adopts cover crops by drainage status and resource region, surveyed corn fields (2016 and 2021)

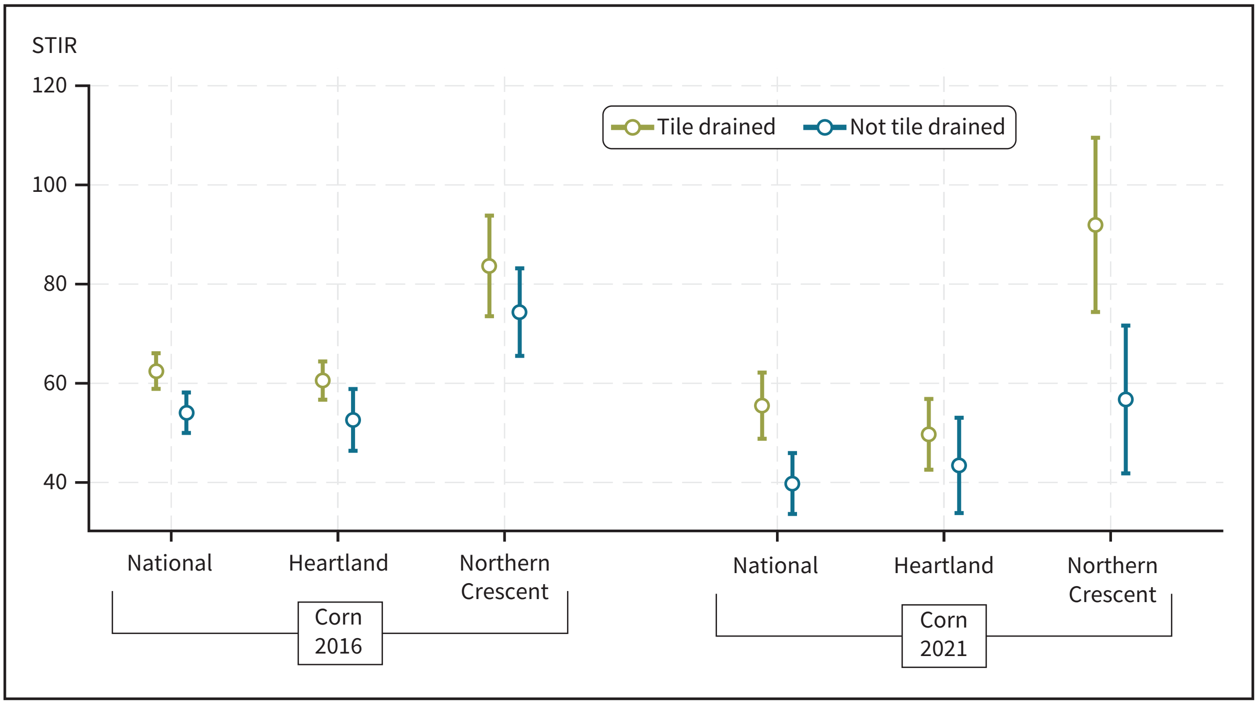


Note: Responses are weighted by USDA ARMS Phase II acreage weights. The vertical lines indicate 95 percent confidence intervals. Acreage percentages are estimated as proportions, hence confidence intervals are calculated using a logit transform so that the bounds lie between zero and one.

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2016 (Corn) and 2021 (Corn) Agricultural Resource Management Surveys (ARMS).

By retaining crop residue on the surface, tillage systems that reduce the intensity of soil disturbance have the potential to reduce soil erosion and surface runoff relative to more conventional forms of tillage. Switching to a conservation tillage or no-till system can result in lower fuel and labor costs to the operator (Claassen et al., 2018a), and under some circumstances increase yields (Wade & Claassen, 2017). However, any benefits to yield and revenue an operator can capture by adopting a no-till system may be limited when operating on a field with poorly drained soil as leaving crop residue on the surface can render the soil too cold and wet for field work. The Soil Tillage Intensity Rating (STIR) index is defined by USDA, NRCS to evaluate the kind, severity, and number of ground-disturbing passes during tillage operations. Values of the STIR index range from 0 to 200, with lower values indicating less soil disturbance (less intensive tillage). The STIR values reported below are calculated from the cumulative field operations reported in the ARMS Phase II data.

Figure 15
Soil Tillage Intensity Rating (STIR) by drainage status and resource region, surveyed corn fields (2016 and 2021)



Note: Responses are weighted by USDA ARMS Phase II acreage weights. The vertical lines indicate 95 percent confidence intervals.

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2016 (Corn) and 2021 (Corn) Agricultural Resource Management Surveys (ARMS).

Nationally, tile-drained acreage experienced higher soil disturbance (more intensive tillage) compared to non-tiled acreage, as indicated by higher average STIR values (figure 15). Regional STIR values for tile-drained acreage were higher than STIR values for non-tiled acreage in the Heartland Resource Region in 2016 ($p < 0.05$) and in the Northern Crescent Resource Region in 2021 ($p < 0.01$). These estimates, along with the estimates indicating higher application rates of nutrients and higher likelihood of fall application, suggest that tile-drained acreage is generally managed more intensively compared to non-tiled acreage. Overall, it is important to note that statistically significant differences in practice adoption between tiled and non-tiled acreage cannot be directly attributed to the presence of a tile system alone, but are most likely also influenced by other factors such as soil type, climate, topography, and production systems that may also be correlated with the adoption of tile drainage. For example, we previously saw that tiled fields on average experience more intensive tillage. Since no-till systems are reported to be less profitable on poorly-drained soils—soils that are more likely to need tile drainage—this empirical finding could reflect the fact that soil and topography influence both drainage and soil management decisions. Therefore, the differences between practice adoption on tiled and non-tiled fields discussed in previous sections should not be interpreted as being the result of tile drainage adoption.

Drainage Control Structures and Drainage Water Management

Drainage water management refers to the use of control structures to hold water in the tile lines during periods when more rapid drainage is not necessary. Drainage control structures allow farmers to manage the timing and amount of water discharged from agricultural drainage systems. Stoplogs in drainage control structures raise the depth of the drainage outlet, elevating the water table on the field. Over the fallow period, the control structure increases water retention in the soil instead of allowing it to drain freely from the tile drain outlet into surface water or another conservation structure. When it is time to begin spring operations, the stoplogs can be removed, and water can outlet through the control structure freely to maximize trafficability when performing field work. During the growing season, the stoplogs can be inserted once again to manage the water table at the desired level (i.e., just below the crop root zone) to store water for use later in the growing season when water may be scarcer. In addition to drainage control structures that use stoplogs to raise outlet height, another type of technology—float-activated head pressure valves—can be installed in tile mains to further increase the water table in the area upstream of the valve (stairstepping the water table up from the outlet control structure). Drainage control structures have been shown to decrease nitrogen and phosphorous loads in subsurface drainage by an average of 46 percent and 36 percent, respectively (see Frankenberger et al. (2023) for a meta-analysis of the literature). Drainage water management reduces nitrate-N discharge by reducing subsurface drainage outflow and by encouraging denitrification on the field (Fouss & Sullivan, 2009). By storing crop-available water during the growing season, control structures can also prevent yield loss in years with dry growing seasons (Baird et al., 2023; Youssef et al., 2023).

Controlled drainage systems do have the potential to increase surface runoff following heavy rainfall in comparison to conventional (non-controlled) drainage (Drury et al., 1996; Skaggs et al., 2010; Lahdou et al., 2019). This tradeoff may have implications for nutrient and pesticide transport (Munster et al., 1995; Singh et al., 2007), although surface dynamics under controlled drainage are understudied in the literature (Mitchell et al., 2023). Furthermore, while conventional (non-controlled) tile drainage is known to reduce nitrous oxide emissions at the field level (Dobbie & Smith, 2006; Grossel et al., 2016), there is limited evidence to suggest that controlled drainage increases nitrous oxide emissions compared to conventional tile drainage (Van Zandvoort et al., 2017; Hagedorn et al., 2022; Zhu et al., 2023).

Drainage water management is best suited on fields with a grade of 1 percent or less. While possible on more steeply sloped fields, more control structures might be required for the same drainage area. Float-activated head pressure valves installed along with the outlet structure can help better control water table levels on sloped fields and prevent tile blowouts (Cooley & Ruark, 2016). Like the installation of drainage systems, the field needs to be large enough to economically justify the installation of a control structure.[10] If a field with a drainage control structure shares a tile system main line with an upstream field, the operator must consider the effects the control structure will have on the upstream field's water table.

Less than 15 percent of tiled corn, soybean, wheat, and oats acreage was equipped with any type of control structure across survey years (stop logs, risers, or float mechanisms) (figure 16). For corn, there was no statistical increase in the proportion of tiled acreage equipped with a control struc-ture from 2016 to 2021 and there was no statistical increase for soybean fields from 2018 to 2023.
As discussed in the next section, subsurface control structures are not a prominent practice in the Environmental Quality Incentives Program (EQIP) in terms of contracts or dollars spent.

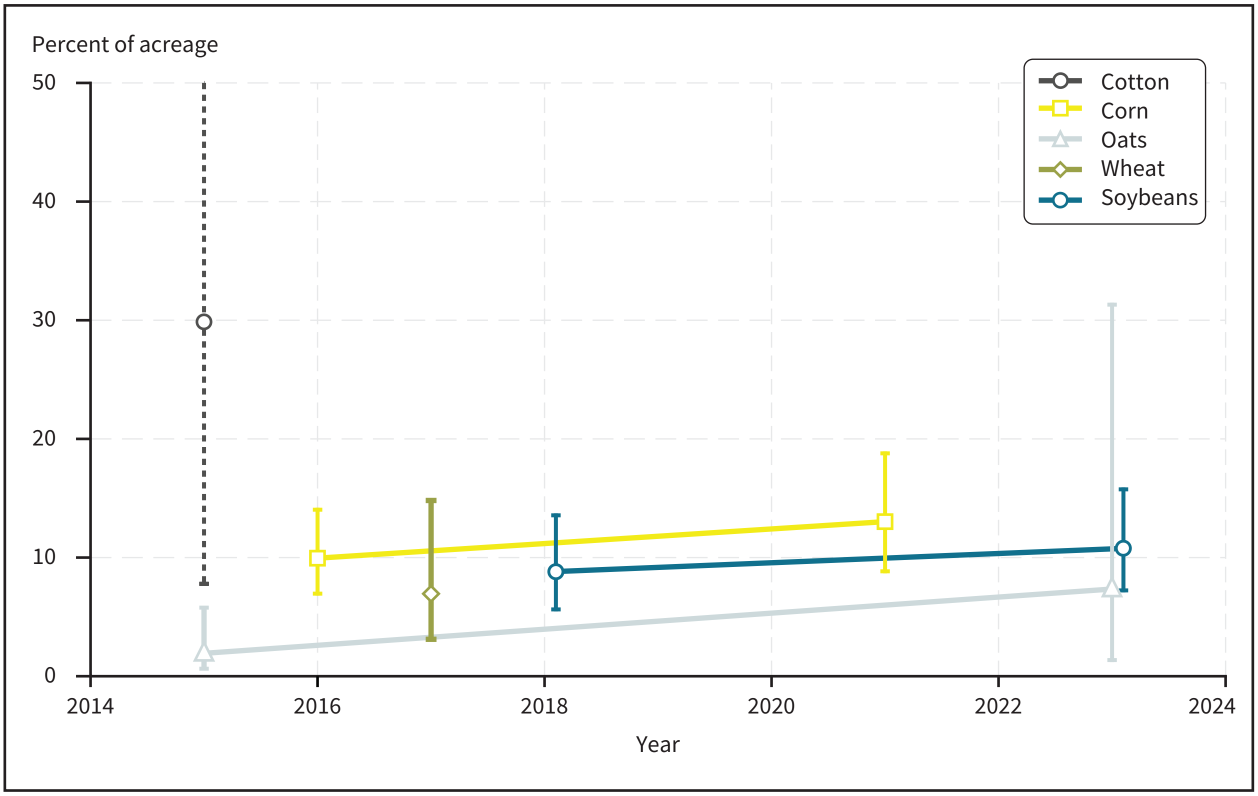
Tile drainage systems with control structures were relatively newer on average across survey years (figure 17), suggesting that newer tile systems may be more likely to be installed with control structures that were historically rare. On average, systems with control structures had an installation date

[10] The Transforming Drainage Project has produced maps indicating land suitable for controlled drainage and uses a minimum field size of 15 acres as a requirement for economic feasibility (Chighladze et al., 2021).

7 years more recent for soybean fields in 2023 ($p < 0.05$), 6.5 years more recent for corn fields in 2021 ($p < 0.10$), 19.75 years more recent for wheat fields in 2017 ($p < 0.01$), 12.7 years more recent for oat fields in 2015 ($p < 0.10$), and 25 years more recent for cotton fields in 2015 ($p < 0.01$). Older systems are less likely to be laid out uniformly across the entire field (pattern tiling), decreasing the effective acreage that would benefit from a single control structure.

Figure 16

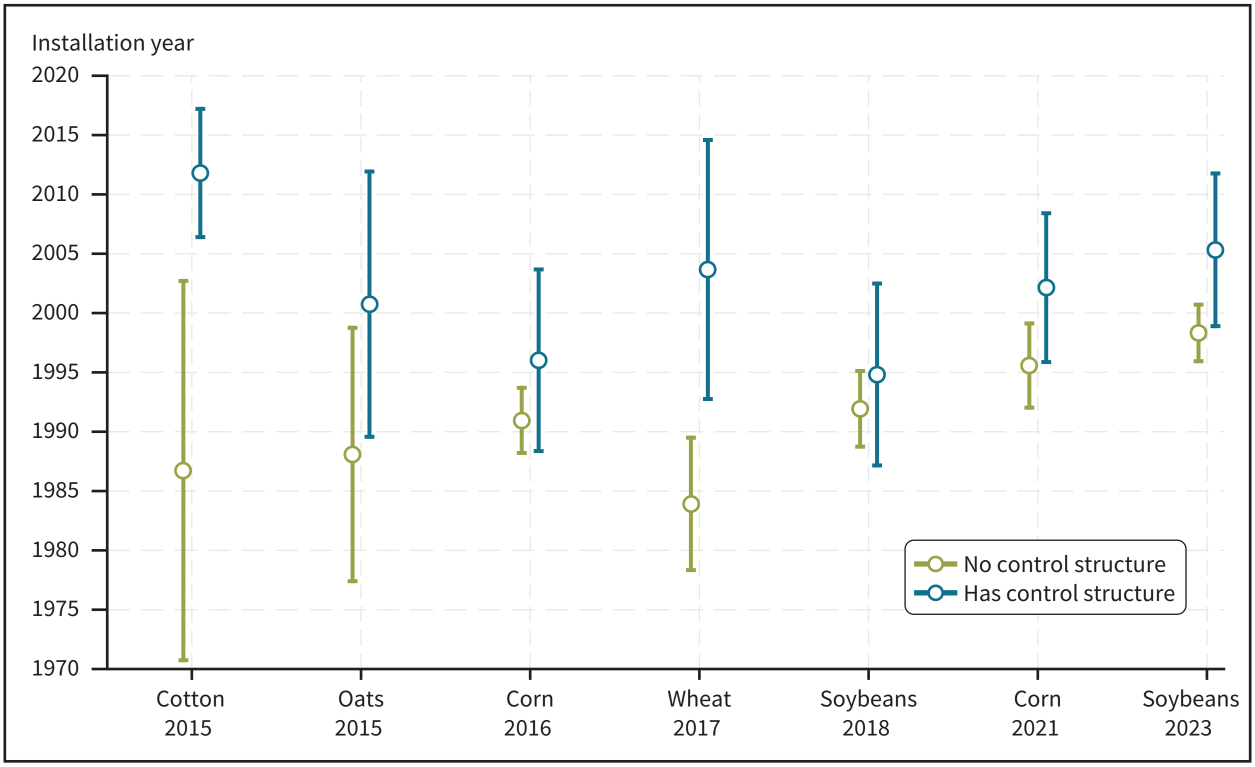
Percent of tiled acreage that has a control structure, by crop



Note: Responses are weighted by USDA ARMS Phase II acreage weights. The vertical lines indicate 95 percent confidence intervals. Acreage percentages are estimated as proportions, hence confidence intervals are calculated using a logit transform so that the bounds lie between zero and one. Questions about control structures were not asked in the 2019 (Cotton) or 2022 (Wheat) surveys. The dashed line for the confidence interval for cotton 2015 indicates that the upper bound of the confidence interval spans values outside the displayed y-axis (the upper bound is 0.68). The question in ARMS is "Does this system include a mechanism for controlled drainage (e.g., stop logs, risers, or float mechanisms)?"

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2015 (Cotton and Oats), 2016 (Corn), 2017 (Wheat), 2018 (Soybeans), 2021 (Corn), and 2023 (Oats and Soybeans) Agricultural Resource Management Surveys (ARMS).

Figure 17
Average installation year of tile system, by presence of a control structure and crop



Note: Responses are weighted by USDA ARMS Phase II acreage weights. The vertical lines indicate 95 percent confidence intervals.

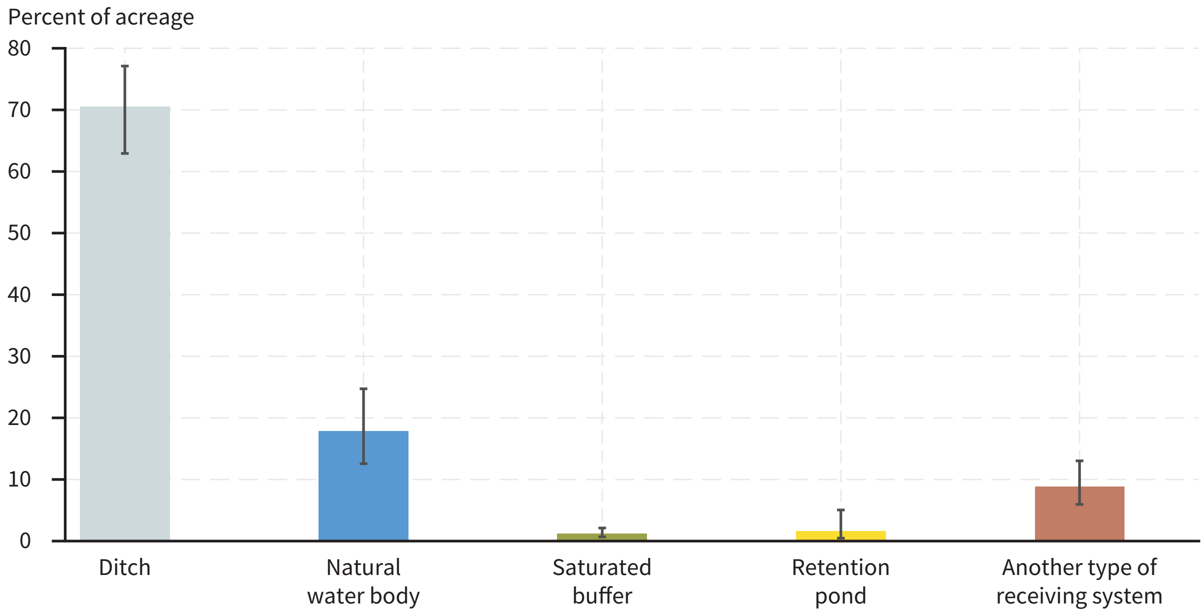
Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2015 (Cotton and Oats), 2016 (Corn), 2017 (Wheat), 2018 (Soybeans), 2021 (Corn), and 2023 (Soybeans) Agricultural Resource Management Surveys (ARMS). Questions about control structures were not asked in the 2019 (Cotton) nor the 2022 (Wheat) survey.

Saturated Buffers and Retention Ponds

Most tile systems empty directly into a drainage ditch or natural waterbody (figure 18). Alternatively, there are several edge-of-field practices that have the potential to decrease nutrient loads to surface water or offer opportunities for drainage water recycling. A saturated buffer is an edge-of-field conservation practice that involves diverting subsurface water via a control structure into a vegetated buffer, where the drainage water first pushes through the buffer's soil before entering the ditch or waterbody. The nitrogen load within the subsurface flow is taken up by vegetation or reduced through denitrification, immobilization, or plant uptake. Saturated buffers have been shown to offer cost effective reductions in nitrate-N levels in subsurface drainage (Jaynes and Isenhart (2019) showed an 8-percent to 84-percent reduction in nitrate levels across 17 buffer site-years in Iowa; Chandrasoma et al. (2022) showed an average 50 percent nitrate loss reduction across 10 buffer site-years in Illinois), with wide potential applicability across the tile-drained Midwest (Chandrasoma et al., 2019). Saturated buffers also require very little or no land to be taken out of crop production.

Subsurface water can also be diverted from a control structure to a pond. Retention ponds can be used to reduce nutrient levels in subsurface outflows through denitrification and nutrient settling. The water (and contained nutrients) can also be recycled back into irrigation or subirrigation systems, potentially increasing crop yields by relieving late-season water deficits (Willison et al., 2020). Saturated buffers and retention ponds are rare today: Less than 5 percent of tiled corn acreage in 2021 and soybean acreage in 2023 were equipped with either practice (figure 18 and figure A.4). Around 9 percent of tiled corn acreage in 2021 emptied into another type of receiving system, which could include other edge-of-field practices not listed explicitly in the survey question—practices such as constructed wetlands, denitrifying bioreactors, or phosphorous removal systems.

Figure 18
Percent of tiled acreage by outlet type, surveyed corn fields (2021)



Note: Responses are weighted by USDA ARMS Phase II acreage weights. The vertical lines indicate 95 percent confidence intervals. Acreage percentages are estimated as proportions, hence confidence intervals are calculated using a logit transform so that the bounds lie between zero and one.

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2021 (Corn) Agricultural Resource Management Survey (ARMS).

Federal Funding for Tile Drainage Modifications

Conservation Practice Standards

The Environmental Quality Incentives Program (EQIP) is USDA, NRCS's main working lands program, offering financial and technical assistance for conservation practice adoption. Through EQIP, farmers and ranchers can enter into contracts and receive payments to adopt Conservation Practice Standards (CPS) to address a variety of resource concerns, including water quality. Conservation Practice Standards include annual management practices and structural practices that have a multi-year lifespan. EQIP is meant to incentivize new practice adoption—fields that have adopted the conservation practice in the past are not eligible.

There are several USDA, NRCS Conservation Practice Standards that aim to mitigate the water quality impacts of tile drainage systems. The cost and payment details associated with each practice can vary across States and fiscal years, as an example we display details for Illinois in fiscal year 2024, including the typical scenario size in practice units, total estimated scenario cost per practice unit, and the general unit cost provided to the EQIP participant (table 2). Subsurface drainage control structures are featured as practice scenarios included under Structure for Water Control (CPS 587). This practice standard also addresses scenarios involving flow meters, culverts, and structures related to irrigation; only a subset of structures installed under CPS 587 are control structures for subsurface flow. Both stoplog outlet structures and float-activated head pressure valves are currently available under the practice standard.

Drainage Water Management (CPS 554) is a practice standard distinct from the installation of the control structure and compensates the producer for the time spent acquiring technical knowledge and actively managing drainage outflow using the control structure. Using the ProTracts database, we find that approximately 75 percent of contracts from fiscal years 2013 to 2024 that featured a subsurface control structure also had at least one accompanying drainage water management payment.

A Denitrifying Bioreactor (CPS 605) is a buried trench, usually filled with woodchips or another carbon material, that subsurface drainage is routed into from a drainage control structure. Bacteria are fed by the woodchips and convert nitrate-N in the water to nitrogen gas. A second stoplog control structure is usually required to control flow from the bioreactor to the receiving ditch or waterbody. Bioreactors have been shown to reduce nitrate-N losses by 20 percent to 40 percent (Christianson et al., 2021). Denitrifying bioreactors were approved as a national CPS in 2015, while Saturated Buffers (CPS 604) were approved nationally beginning in fiscal year 2017.[11] Both practices are often coupled with Structure for Water Control (CPS 587) for the subsurface control structure(s) required for the implementation of the practices. Like saturated buffers, bioreactors can be installed without taking land out of crop production.

The Irrigation Tailwater Recovery practice standard involves the collection, storage, and reuse of irrigation runoff (tailwater) to improve water use efficiency. This standard was expanded to include practice scenarios addressing drainage water in 2020 and is now titled Irrigation and Drainage Tailwater Recovery (CPS 447). Under the practice scenario for drainage water recycling, subsurface drainage is stored in a retention pond, which can be constructed separately following the pond practice standard (CPS 378). A sump and pipeline system recycles the drainage water from the pond first to a storage tank, then back up through the tile system where the water and nutrients can be retained and reused on the field with a control structure. Through fiscal year 2024, no contracts featuring Irrigation and Drainage Tailwater Recovery have addressed drainage water. Since 2020, the only contracts containing this practice have been written in Arkansas and California and have exclusively addressed irrigation tailwater recovery.[12]

A Constructed Wetland (CPS 656) is an artificial wetland constructed for the purpose of treating agricultural runoff or drainage discharge. Under the most common practice scenarios in the Midwest, the CPS involves the excavation of a 1-acre wetland of an average depth of 18 inches with hydrophytic vegetation either planted or established through natural regeneration. In the design of the wetland, USDA, NRCS assumes that one half of the area of the wetland is land that is taken out of crop production. Subsurface flows are routed to the wetland, where denitrification and nutrient settling take place before the water is discharged. Like the preceding practices, a constructed wetland often needs to be accompanied by a control structure under CPS 587. Gordon et al. (2021) found a 67-percent decrease in nitrate-N in subsurface discharge treated by a constructed wetland.

[11] Bioreactors were previously listed under code 747 as an interim practice standard before 2015. Saturated buffers were previously listed under code 739 as an interim practice standard before 2017.

[12] Not all States include drainage water recycling as an available scenario under CPS 447. For example, as of fiscal year 2024, while Iowa, Missouri, Illinois, Indiana, and Ohio offer the scenario, Minnesota, Wisconsin, and Michigan do not.

A Phosphorous Removal System (CPS 624) consists of an edge-of-field structure that removes dissolved reactive phosphorous from drainage discharge. The structure contains a media that absorbs phosphorous and filters drainage water as it flows through the structure. Phosphorous removal structures can take several different forms depending on the site context, including a filter tank and filter beds for subsurface drainage, and have been shown to reduce dissolved phosphorous concentrations and loadings by 16–71 percent (Penn et al., 2017; Ohio State University Extension, 2021).

Conservation Practice Standards addressing subsurface drainage can also provide co-benefits beyond reducing nutrient leaching. Ponds accompanying Drainage Tailwater Recovery (CPS 447), as well as constructed wetlands (CPS 656), have the potential to capture and retain surface runoff in addition to subsurface flow, as well as provide wildlife habitat and aesthetic or recreational value. In addition, bioreactors have the potential to remove other pollutants besides nitrate-N, including phosphorous and pesticides (Mitchell et al., 2023). Several conservation practices addressing subsurface drainage qualify as mitigation measures that address pesticide transport under the U.S. Environmental Protection Agency's (EPA) Endangered Species Protection Program, including control structures, saturated buffers, and ponds (EPA, 2025). The Endangered Species Protection Program aims to reduce the exposure of federally listed endangered and threatened species to commonly used insecticides, herbicides and rodenticides.

Table 2

USDA, Natural Resources Conservation Service (NRCS) Conservation Practice Standards related to tile drainage systems

Practice name	Practice code	Estimated scenario size	Total estimated scenario cost per unit	General unit cost provided	Potential yield impacts
Saturated buffer	604	400 feet of dispersal conduit	$13.22 per foot	$9.91	Minimal
Denitrifying bioreactor	605	366 cubic yards of carbon source	$79.49 per cubic yard	$59.62	Minimal
Structure for water control	587	1 control structure	$2,443.90 per structure	$1,833.13	Positive
Drainage water management	554	5 control structures	$178.53 per structure	$133.89	Positive
Irrigation and drainage tailwater recovery	447	1,150 feet of recirculating pipe	$28.91 per foot	$21.68	Positive
Constructed wetland	656	1 acre	$14,729 per acre	$11,102.92	Minimal
Phosphorous removal system	624*	28 cubic yards of media	$214.80 per cubic yard	$161.21	Minimal

Note: All practices are adapted from USDA, NRCS Illinois Fiscal Year 2024 except the Phosphorus Removal System, which is taken from Indiana Fiscal Year 2024. The size and cost terms correspond to the following practice scenarios—Saturated Buffer Scenario #2: Saturated Buffer; Denitrifying Bioreactor Scenario #5: Denitrifying Bioreactor with liner, no soil cover; Structure for Water Control Scenario #9: Inline WCS, Subsurface Drainage Control, <=10 inches diameter pipe; Drainage Water Management Scenario #12: Manual Drainage Water Management; Irrigation and Drainage Tailwater Recovery Scenario #3: Drainage Water Recycling; Constructed Wetland Scenario #1: Constructed Wetland, Dense Planting; Phosphorous Removal System Scenario #7: In-Ditch Filter or Tile Discharge.

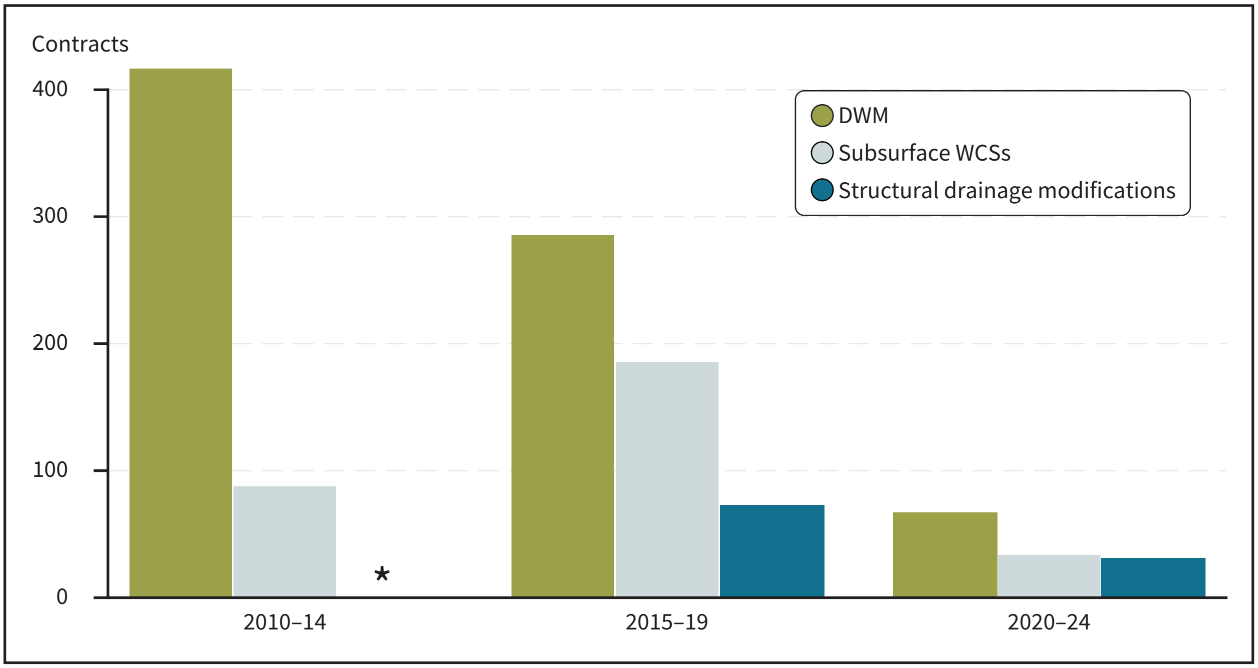
* Phosphorous Removal System was under interim practice standard CPS 782 in fiscal year 2024.

Source: USDA, Economic Research Service using USDA, Natural Resources Conservation Service (2023a, 2023b, 2023c, 2023d).

Contracts and Financial Assistance

Funding availability for a particular conservation practice is shaped by national, State, and local USDA, NRCS offices, USDA, NRCS State Technical Committees, and local working groups who establish the priority resource concerns that EQIP contracts should address (Wallander et al., 2019). Since EQIP is voluntary, the number of contracts containing a practice is also dependent on the level of interest expressed by farmers and ranchers. Contracts containing drainage water management and/or subsurface water control structures are relatively uncommon and have been decreasing since the late 2010s (figure 19). This, however, should not be interpreted as a decrease in or lack of EQIP contracts addressing nutrient leaching, as there are several other conservation management practices that address the issue and that have been heavily featured through EQIP across the time period, including cover crops (CPS 340) and nutrient management (CPS 590) (Rosenberg et al., 2024).

Figure 19
Contracts containing Conservation Practice Standards (CPS) related to subsurface drainage



DWM = Drainage Water Management (CPS 554). Subsurface WCSs = Subsurface Water Control Structures (CPS 587).

Note: Structural Drainage Modifications aggregates contracts for saturated buffers, constructed wetlands, phosphorous removal systems, and bioreactors. The number of contracts in a range of fiscal years corresponds to the new contracts obligated during that range. Subsurface control structures were isolated from all implementations of CPS 587 recorded in the ProTracts database. Since contracts can include more than one practice, the three bars in a given year range cannot be added, as it would result in double- or triple-counting of certain contracts.

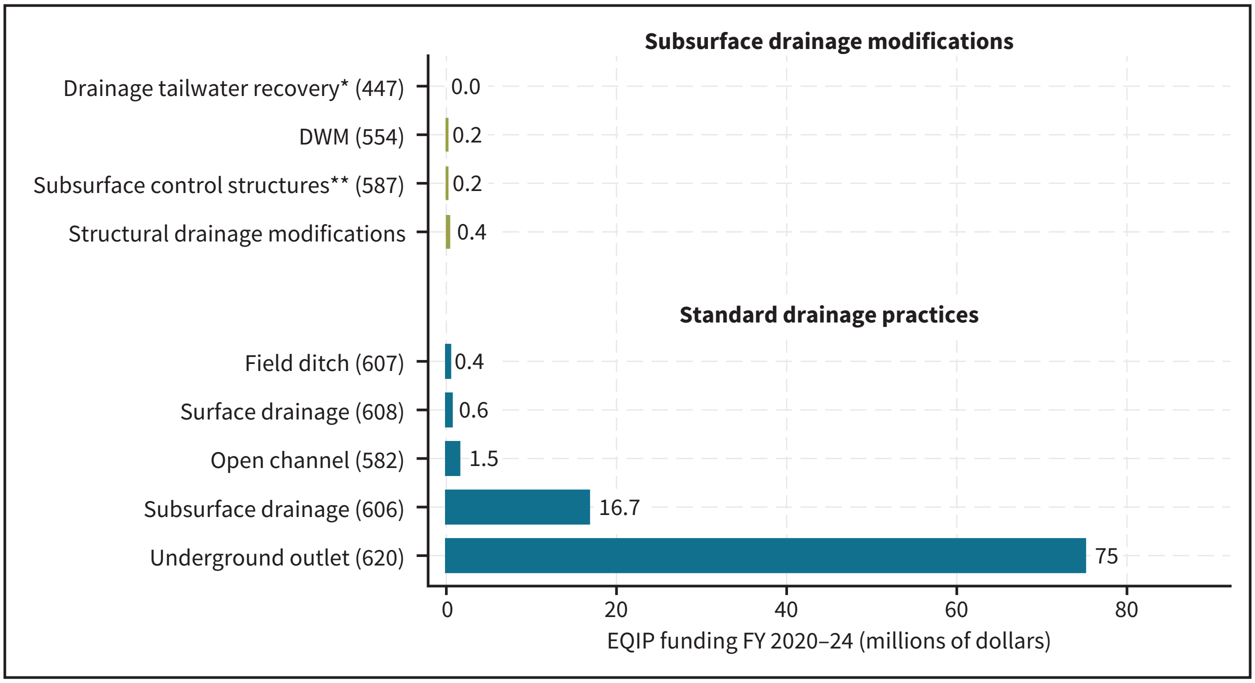
* All yearly contract totals of 10 or less are censored for disclosure purposes.

Source: USDA, Economic Research Service based on USDA, National Resources Conservation Service, ProTracts database.

Contracts containing saturated buffers, constructed wetlands, phosphorous removal systems, or bioreactors are rare. For disclosure concerns, we aggregate the four practices into a combined Structural group in our figures. The concept of additionality, or the degree to which adoption of a conservation practice would not have occurred in the absence of the financial assistance, is a key metric for voluntary conservation programs (Claassen et al., 2014). These practices can be considered as some of the most additional practices offered by USDA, NRCS, as it is highly likely the operator would not have implemented a saturated buffer, wetland, phosphorous removal system, or bioreactor in the absence of EQIP financial assistance. Edge-of-field structural practices, given their cost and lack of immediate financial benefits to the adopter, have been found to be highly additional (Claassen et al., 2018b). Generally, practices that primarily generate benefits that accrue off farm with few or no on-farm benefits to the adopter are the least likely to be adopted without financial assistance.

Figure 20

Environmental Quality Incentives Program (EQIP) financial assistance for various Conservation Practice Standards, fiscal years (FY) 2020–24



DWM = Drainage Water Management. IWM = Irrigation Water Management.

Note: Structural drainage modifications aggregates funding for saturated buffers, constructed wetlands, phosphorous removal systems, and bioreactors. For Conservation Practice Standards 447 and 587, marked with * and ** respectively, the numbers refer to funding for the practice that was allocated to practice scenarios related to tile drainage, filtering out funding for the practice that related to irrigation or surface water.

Source: USDA, Economic Research Service based on USDA, National Resources Conservation Service, ProTracts database.

EQIP also provides financial and technical assistance for the installation of standard subsurface drainage systems, as well as surface drainage systems. From fiscal years 2020 to 2024, the financial assistance going towards the installation of subsurface drainage has been greater than the combined financial assistance going towards saturated buffers, constructed wetlands, phosphorous removal systems, subsurface control structures, drainage water management, bioreactors, and drainage tail-water recycling (figure 20). Contracts with Subsurface Drainage (CPS 606) often also include practices that reduce nitrate leaching, such as Cover Crops (CPS 340) or Nutrient Management (CPS 590).

Conclusion

The proliferation of tile drainage systems has allowed for the flat, poorly drained soils of the Midwest to host some of the most productive agricultural land in the world. Millions of miles of corrugated piping installed under the soil support the viability of tens of millions of acres of corn and soybean rotations in the Midwest, providing grain for human consumption, livestock, and energy. Without tile, much of the acreage in the Midwest would be unable to accommodate the planting dates modern cultivars require to maximize yield over the growing season. These tile drainage systems also act as a conduit for the delivery of leached nitrate-N and dissolved reactive phosphorous to downstream surface bodies—nutrients that contribute to the hypoxic zone in the Gulf of America. This report details trends in tile-drained acreage and characterizes how certain management and conservation practices are utilized on tile-drained fields compared to non-tiled fields. The Census of Agriculture reveals an expansion of tiled acreage since 2012, predominantly in the Corn Belt and the upper latitudes of the Midwest. Field-level data from ARMS for corn production suggests that tile-drained acreage is managed more intensively compared to non-tiled acreage, as indicated by higher application rates of total fertilizer, higher rates of fall fertilizer application, and higher soil disturbance through tillage. Tile-drained acreage is also twice as likely to see application of nitrification inhibitors. The evidence also points to intensification of tile drainage systems in certain regions in the past decade, accompanied by low adoption rates for interventions that reduce the transport of leached nutrients such as control structures, saturated buffers, and retention ponds.

Addressing nutrient transport in the tile-drained Midwest remains a policy priority. The Hypoxia Task Force is a Federal, State, and tribal collaborative partnership created in 1997 to reduce nutrient pollution in the Mississippi/Atchafalaya River Basin and the size of the hypoxic zone in the Gulf of America (Porter et al., 2015). A primary activity of the Task Force is the implementation of State-specific nutrient reduction plans. Further economics research on the drivers of tile adoption, drainage intensification, as well as policy and program design can support these functions. Lack of data, however, is a barrier. Greater information on subsurface drainage systems is often unavailable due to their age—landowners and operators may be uncertain about the detailed characteristics of their system, especially if the systems consist of the original clay tile installed many decades ago. Furthermore, while some jurisdictions require permits for the installation of tile drainage systems, data on permits are often limited and not spatially explicit. In the past decade, remote sensing has been utilized to predict the presence of tile drainage on the landscape. Data products mapping out tile drainage at a more spatially disaggregated level have been developed to further disentangle the effect of tile on nutrient transport and watershed hydrology.[13] Use of remotely-sensed drainage data by the agricultural economics community can advance the descriptive analysis in this report by enabling the estimation of causal relationships between tile drainage adoption and economic and environmental outcomes.

[13] For example, the Transforming Drainage Project produced 30-meter resolution datasets of drainage extent in the Midwest based on the USDA, NRCS Soil Survey (Frankenberger et al., 2022). Other tile drainage mapping products include Nakagaki et al. (2016), Valayamkunnath et al. (2020), Jame et al. (2022), and Wan (2024).

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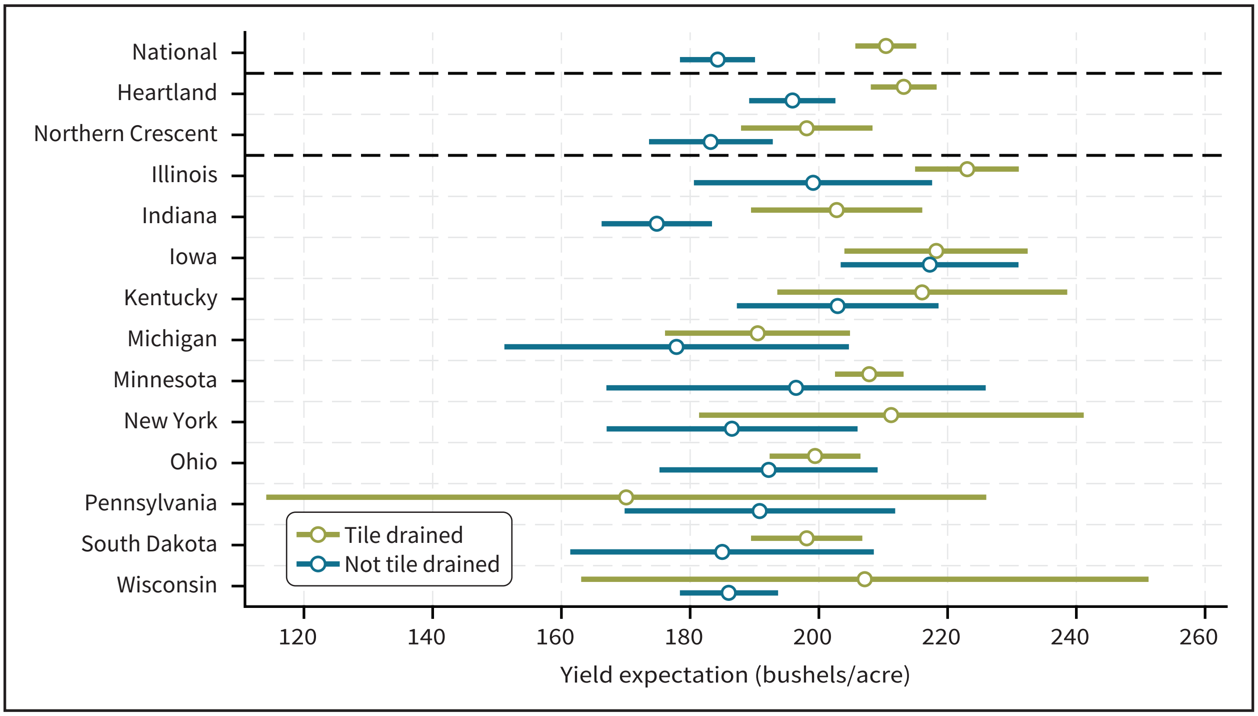
Appendix A: Additional Figures

Yields

We can also use observational field-level survey data from the Agricultural Resource Management Survey (ARMS) to compare expected yields for tiled fields verses non-tiled fields. Respondents were asked what their yield goal was, at planting, for the selected field. Nationally, tiled corn fields in 2021 had an expected yield 26 bushels per acre or 14 percent larger, on average, compared to non-tiled fields ($p < 0.01$) (figure A.1). Estimates for average expected yield are also displayed for individual States, and for the two USDA, Economic Research Service (ERS) Farm Resource Regions with the most tile drainage—the Heartland and the Northern Crescent (figure A.2). In the Heartland region (much of the Midwest), tile-drained corn fields had an expected yield 17 bushels per acre or 8.8 percent larger, on average, compared to non-tiled corn fields ($p < 0.01$).

Figure A.1
Average yield expectations by drainage status, survey corn fields (2021)



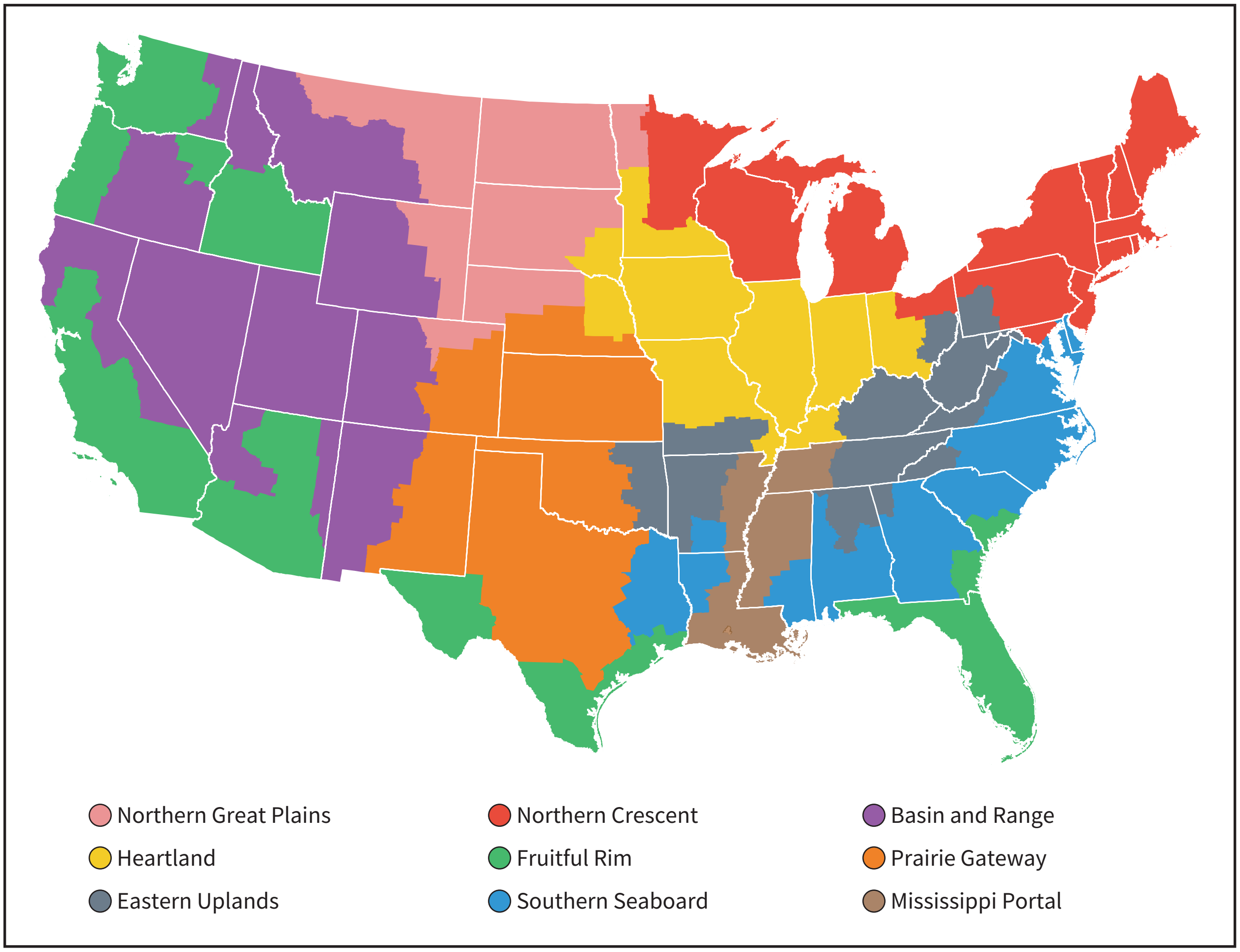
Note: Responses are weighted by USDA ARMS Phase II acreage weights. The horizontal lines indicate 95 percent confidence intervals.

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2021 (Corn) Agricultural Resource Management Survey (ARMS).

An important caveat for interpreting survey data: While ARMS allows us to observe statistical differences across the two sets of fields, unlike experimental plots we cannot ensure all other factors are comparable across the two sets and that any difference in yield expectations is due to the presence of tile drainage on the field. In addition, there is potential selection bias—many fields that do not have tile now are probably well-drained and have been deemed less likely to benefit from tile by the landowner. Therefore, while through ARMS we can associate tile drainage with more productive fields, we cannot conclude that tile drainage alone is the reason behind the difference in productivity, or that the non-tiled estimates are a good representation of what the tiled fields would look like in the absence of tile drainage.

Figure A.2

USDA, Economic Research Service (ERS) Farm Resource Regions

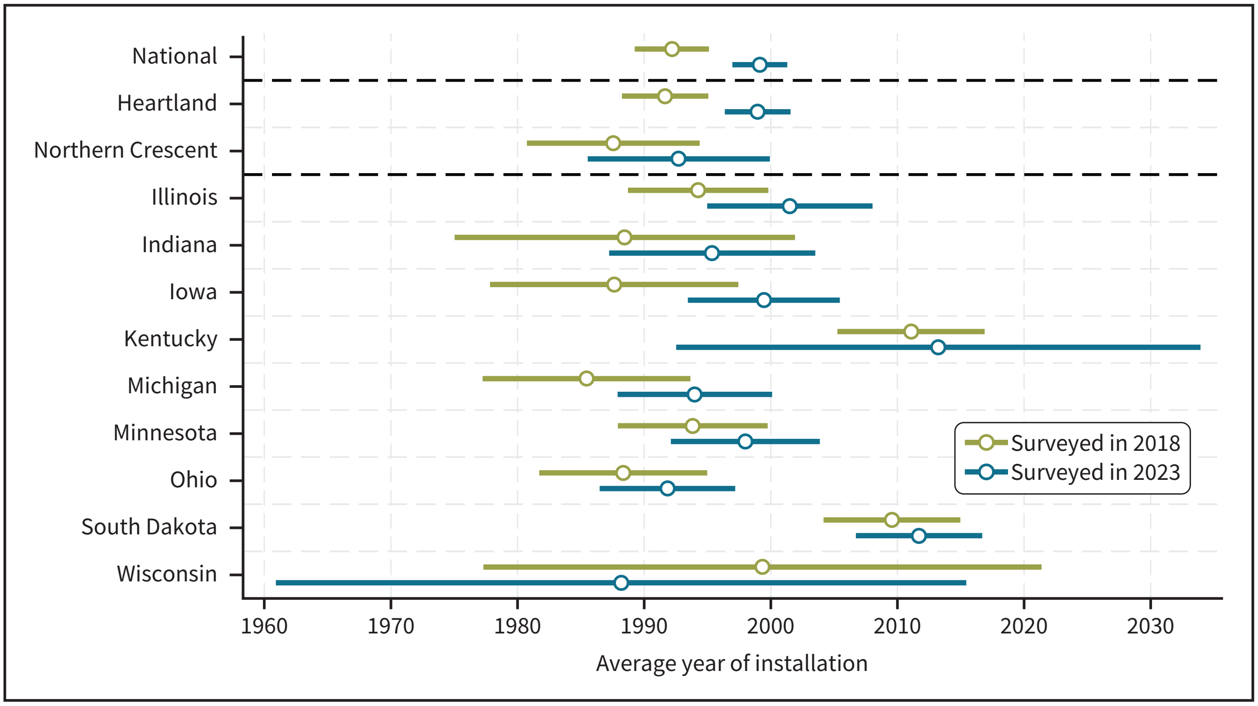


Note: USDA, Economic Research Service (ERS) Farm Resource Regions do not include Alaska and Hawaii because they are not included in USDA, ERS and USDA, National Agricultural Statistics Service's Agricultural Management Resource Survey (ARMS).

Source: USDA, Economic Research Service using Heimlich (2000).

Figure A.3

Average year of tile drainage installation, surveyed soybean fields (2018 and 2023)

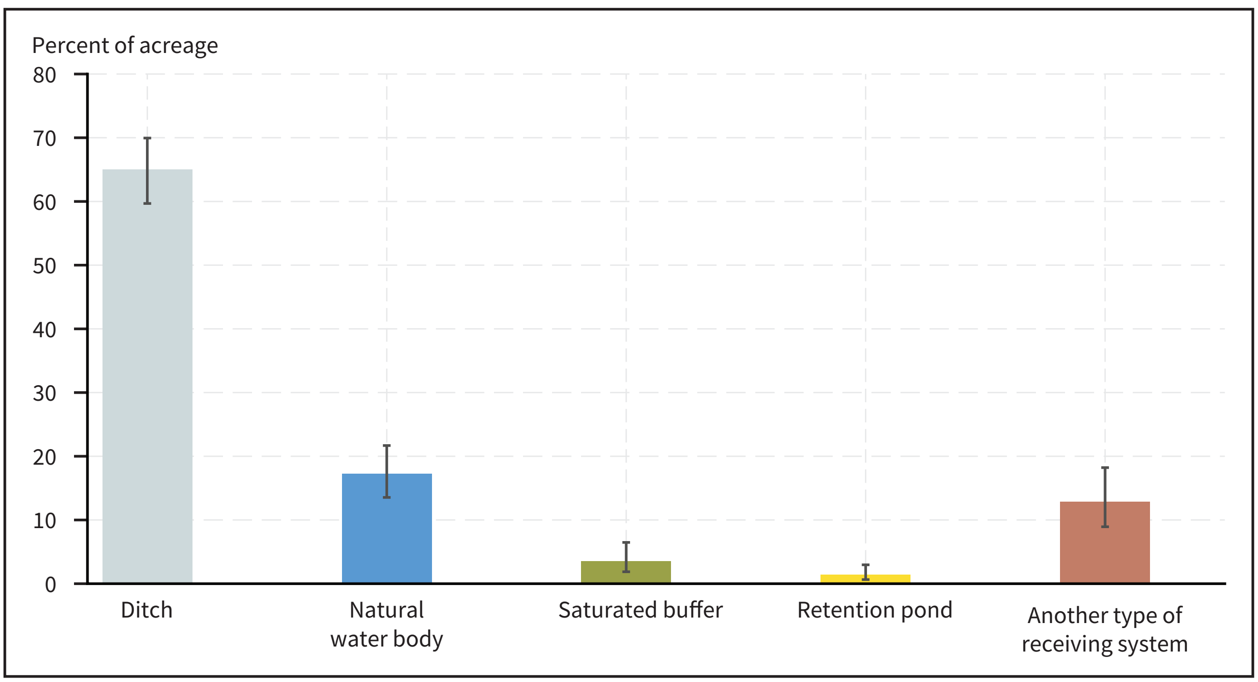


Note: Responses are weighted by USDA ARMS Phase II field-level survey weights. The vertical lines indicate 95 percent confidence intervals.

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2018 (Soybeans) and 2023 (Soybeans) Agricultural Resource Management Surveys (ARMS).

Figure A.4

Percent of tiled acreage by outlet type, surveyed soybean fields (2023)



Note: Responses are weighted by USDA ARMS Phase II field-level survey weights. The vertical lines indicate 95 percent confidence intervals.

Source: USDA, Economic Research Service and USDA, National Agricultural Statistics Service, 2023 (Soybeans) Agricultural Resource Management Survey (ARMS).

Appendix B: Acronyms and Abbreviations

ARMS = Agricultural Resource Management Survey

CPS = Conservation Practice Standard

DSFW = Days Suitable for Field Work

DWM = Drainage Water Management

EQIP = Environmental Quality Incentives Program

ERS = USDA, Economic Research Service

IWM = Irrigation Water Management

NRCS = USDA, Natural Resources Conservation Service

STIR = Soil Tillage Intensity Rating

USDA = U.S. Department of Agriculture